THE EFFECTS OF KNOWLEDGE VERSUS PRODUCTION BOUNDARIES ON FIRM SURVIVAL THROUGH SYSTEMIC TECHNOLOGICAL CHANGE

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Firms that develop complex products are at greater risk from systemic technological change, which alters the way product components work together, and can also affect the nature of demand for a product. We ask what combinations of knowledge and production boundaries best position firms that make complex products to survive systemic change. Some work suggests that vertical integration might improve survival but other research posits that maintaining broad knowledge boundaries could be sufficient, as it enables efficiency through outsourcing yet retains effectiveness in integrating component technologies. We propose that the answer depends on whether we focus on technological or market boundaries, and that while in general broad boundaries favor adaptation to systemic change, integrating downstream from manufacturing can hinder adaptation. In addition, we argue that integration into the manufacture of components may be more critical than is suggested in prior work. Our longitudinal study of systemic change in the hard disk drive industry provides preliminary support for these predictions.

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PREFACE

I first want to thank my mom, Colleen Woroniecki, who has always been my biggest supporter. I don't know what I would do without you, I could never wish for a better Mom. I also want to thank my brother Eric and my aunts, uncles and cousins for always keeping me grounded and cheering me on.

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DEDICATION

This dissertation is dedicated to my cousin, Shaun Patrick Walsh (1985-2012), whose life was cut much too short.

1.0 INTRODUCTION

A small but promising stream of research has argued that firms can 'know' more than they 'do' and has suggested that this might be a beneficial configuration of organizational boundaries for complex products comprised of many component technologies (e.g. Brusoni, Prencipe, Pavitt, 2001; Granstrand, Patel, & Pavitt, 1997; Prencipe, 1997). While firms may be incapable of efficiently producing all of the components comprising complex products (i.e. they might lack the requisite scale or relevant skills), they nonetheless need to understand the component technologies to effectively integrate them (Brusoni et al., 2001; Ciravegna and Maielli, 2012; Henderson & Clark, 1990; Takeishi, 2002).

Empirical evidence supporting this argument, however, remains elusive. Previous studies on firms' *production* boundaries—defined as the degree to which firms have integrated into the manufacturing of component technologies (Brusoni, et. al., 2001; Granstrand, Patel, & Pavitt, 1997; Sorenson, 2003) and distribution and sales activities (Anderson and Schmittlein, 1984; John and Weitz, 1988; Rothaermel, 2001, 2005)—offer conflicting evidence as to whether broad or narrow production boundaries provide adaptive advantages in the face of technological change[1]. While some studies found a positive effect for broad production boundaries (e.g. Negro

[1] Studies have more often focused on technological uncertainty. Balakrishnan (1986), Harrigan (1984, 1985), Jones and Hill (1987), Sorenson (2003), John and Weitz (1988) and Klein, Frazier Roth (1990) focus on environmental volatility without typifying its different sources and specific effects. Tripsas (1997), Rothaermel (2001, 2005) focus on technological change that is competence destroying, while Kapoor and Adner (2012) focus on architectural and

and Sorenson, 2006; Sorenson, 2003), others found negative effects (e.g. Balakrishnan and Wernerfelt, 1986; Adner and Kapoor, 2010; Afuah, 2001). The situation becomes further complicated when products are technologically complex, i.e. comprised of component technologies that may change at different speeds. While transaction cost economics ('TCE') explains firms' production boundaries as resulting from firms' efforts to govern individual transactions efficiently (Williamson, 1985), governance modes that are efficient for individual transactions (i.e. manufacturing of individual components) are not necessarily efficient for managing system-level outcomes. For example, to accommodate new component technologies firms might need to alter their product architectures and manufacturing processes, the technological systems that support a product line. They might also need to adapt the set of activities used to market and sell new products and to educate and learn from customers, the commercialization systems that support a product line.

Recent studies have further suggested that a firm's knowledge boundary choices may enhance a firm's ability to manage change to a firm's technological systems (e.g. Brusoni et al., 2001; Ciravegna and Maielli, 2012; Takeishi, 2002). A firm's *knowledge boundaries* are defined by the content domains a firm understands, and are reflected in codified knowledge and knowledge that resides within employees and a firm's routines (Butler, 2012; Carlile, 2002; Garicano, 2012; Grant, 1996; Kogut, 1996). Broader knowledge boundaries (i.e. knowing about more content domains) allow firms to successfully outsource the production of product components while still maintaining the capability for integrating them into the product (a key technological system) (Brusoni et al., 2001; Ciravegna and Maielli, 2012; Takeishi, 2002). In

component enabled technological change. We focus on technological change that alters critical relationships comprising the technology and commercialization systems that are integral to a firm's ability to serve particular customers, and hence the firm's performance in a market.

addition, studies have found that firms need to have a broad knowledge base in place to incorporate new technologies that have system-wide ramifications (i.e. cause or require other components and subsystems to be redesigned) (e.g. Ciravegna and Maielli, 2012; Takeishi, 2002). Thus, knowledge boundary choices are a critical aspect of firms' capacities to manage systemic change.

Beyond these important insights, however, unresolved questions remain. With one notable exception (Kapoor and Adner, 2012), prior research has failed to provide a clear set of contingencies for when broad or narrow organizational boundaries are appropriate. Moreover, studies have not considered how the knowledge and production boundaries that affect market and technology systems might *jointly* affect firms' capacities to adapt to systemic technological change. While some prior work stresses the importance of communication between knowledge-producing activities and traditional production functions for fostering the organizational capabilities that are needed to adapt to technological change (Hoetker, 2005; Takeishi, 2002), even this work fails to address what happens when technological change necessitates adaptation in both the technology and market systems which support a product class. Moreover, studies in the TCE paradigm (in which most research on production boundaries is grounded) rarely distinguish the types of technological change firms might confront and instead measure technological uncertainty simply as volatility. This approach is problematic as it risks conflating many different kinds of technological change with distinctive organizational and contractual implications.

In sum, it remains unclear from the existing literature whether broad knowledge boundaries, broad production boundaries, or some combination of each will better prepare a firm to adapt to technological change that disrupts established technology and market systems.

Addressing these open issues, our study's intent is to develop a better understanding of how a firm's boundary choices affect its adaptive capacities in industries that are characterized by frequent, systemic changes. In particular, we examine how the breadth of a firm's knowledge boundaries and whether a firm has narrow or broad production boundaries determine a firm's survival prospects through systemic changes that affect a firm's technological and market systems. By examining their independent and joint effects, we shed light on the ambiguous findings in prior work on the adaptation benefits of boundary choices regarding one or the other. We further go beyond prior work to investigate the different effects of knowledge and production boundaries regarding the technology and markets a firm participates in. We specifically focus on a setting where technological change has frequently disrupted the product architectures and manufacturing systems supporting a complex product, as well as the market systems used to commercialize it. During the time period we study, standards that specify how component technologies would interface with one another alternated between closed, proprietary and open standards, prompting dramatic shifts in firms' organizational boundary choices.

Our theory is supported by our findings. We find that broad technology production boundaries increase a firm's chances of survival, and have an enhanced effect on firm survival when paired with broad technology knowledge boundaries. We further find that broad market knowledge boundaries increase a firm's survival odds, but have a decreased effect on firm survival when paired with broad market production boundaries.

Our study makes several contributions to the literature. We illustrate that when firms encounter systemic change, their market boundaries confer adaptive advantages or disadvantages differently than do their technological boundaries. Broad technology production boundaries increase a firm's survival, but broad market production boundaries do not. We also add to the literature which examines performance trade-offs associated with a firm's vertical boundaries. Specifically, we show that broad market knowledge boundaries can offset the adaptive disadvantages associated with broad market production boundaries. Although the statistical significance is weaker (reflecting measurement challenges), our findings suggest that broad technological knowledge augments the adaptive advantages of broad technological boundaries. Our study extends recent work that seeks to understand how knowledge and production boundaries affect firm capabilities for adaptation and innovation by including market boundaries and by studying a firm's survival through systemic change. Unlike in notable previous studies (e.g. Kapoor and Adner, 2012; Brusoni, et. al., 2001), in the context we studied, systemic change frequently altered the relevant metrics for assessing product performance.

1.1 THEORETICAL BACKGROUND

1.1.1 Typology of Technological Change

The literature identifies a variety of ways that technological change disrupts[2] established systems. Henderson and Clark (1990) introduced the term architectural innovation, in which knowledge about individual components is still relevant, but knowledge about component interactions is no longer relevant. Tushman and Anderson (1986) describe a competence-destroying technological discontinuity as a situation where the processes, skills, and knowledge

[2]These authors (Christensen, 1993; Henderson and Clark, 1990; Tushman and Anderson, 1986) refined the definition of technological uncertainty into different categories to indicate how large the change was from either a firm level or market-level perspective. Smaller changes were considered incremental, while larger changes were considered radical.

bases for an older technology are no longer relevant or have become dramatically less valuable in a particular market. Christensen (1993) describes disruptive change as a shift in the criteria which define the dominant trajectory of performance improvement in established markets.

Each of these typologies highlights important aspects of technological change that are likely present to varying degrees in most substantive innovations. The label architectural innovation has been used to emphasize change in the technological systems – particularly how components relate to one another (Henderson and Clark, 1990; Christensen, 1992; Henderson and Cockburn, 1994), while competence-destroying innovation encompasses the routines and processes comprising an organizational system (Cooper and Schendel, 1976; Tushman and Anderson, 1986, 1990). Disruptive innovation, as Christensen (1993) uses the term, emphasizes how innovation can challenge established market systems.

We define *systemic change* as a technological change that disrupts one (or more) of three systems that support a firm's product line: the *technological system*, which delimits what a firm can make and includes the knowledge embodied in the R&D function and the products it produces, as well as manufacturing knowledge and the processes which comprise this function (e.g. Tushman and Anderson, 1986; Henderson and Clark, 1990); the *organization system*, which defines how a firm accomplishes and coordinates R&D and manufacturing through structure and routines (e.g. Hannan and Freeman, 1984; Christensen and Overdorf, 2000; Rosenberg, 1976); and the *market system*, which defines how a firm reaches a market and derives profits from it, including its approach to marketing and distribution (e.g. Tripsas, 1997; Christensen and Rosenbloom, 1995; Rothaermel 2001, 2005). We focus on disruptions to the technological and market systems (see Figure 1 for a diagram of organizational systems/functions that can be affected by systemic change). Appendix C summarizes studies that address change in the three systems.

Figure 1. Organizational Systems/Functions Affected by Systemic Change

1.1.2 Systemic Change's Effects on a Firm's Systems

Systemic change occurs in a firm's *technological systems* when the components of a system – whether it be the product or the processes used to manufacture it – must relate to each other in a new way (Henderson and Clark, 1990; Henderson and Cockburn, 1994). Although much of the firm's knowledge base may still be relevant, to adapt, firms must overcome organizational inertia to engage in new problem-solving processes and to determine how to realign the components of the system (Henderson and Clark, 1990; Rosenberg, 1976; Tushman and Andersen, 1986). Systemic change occurs frequently in complex products, which are comprised of multiple components progressing technologically at different rates, and remains a challenge for firms in high-tech industries (Brusoni, et. al, 2001). Firms that offer complex products may need to redesign the device each time a component technology shifts and affects how other components function, as this type of change alters their joint influence on the performance of the product. Systemic technological change also presents a significant challenge for firms' manufacturing choices, as relates to its technological systems. Manufacturing methods may shift to new processes with new materials, and new parameters and specifications may be necessary for making each component, in order for these components to interface correctly within the device.

Systemic change can also affect a firm's market system by creating new markets, with new customer bases and corresponding customer needs. A firm's *market system* consists of a firm's investments in marketing, distribution, and sales networks and the accompanying market knowledge bases to commercialize its technological products. Christensen and Rosenbloom (1995) describe a firm's commercialization system as "the context within which a firm competes and solves customer problems," which focuses a firm on creating value for its existing customers. A firm's market/commercialization system and its market knowledge base may discourage it from investing in new markets that seem too small to be commercially viable. Firms may require knowledge that helps them to recognize emerging opportunities (e.g. Chesbrough, 2003; Laursen and Salter, 2006; Zhou and Li, 2012) with different customer needs, applications and requirements as compared to the existing customer base (Christensen, 1993; Christensen and Rosenbloom, 1995).

Finally, systemic change can affect a firm's *organizational system*, the routines and processes through which a firm researches, designs, develops, and delivers its products to customers. In order to adapt to systemic change, firms may need to change their organizational structure and routines to accommodate the shifts in R&D and manufacturing. Firms may actually be limited in their ability to respond to change by their existing methods of coordination, decision-making, and communication that are rigid and have evolved over a long period of time.

Systemic change creates new opportunities for firms to profit, but organizational processes may inhibit firms' abilities to recognize the opportunities and respond appropriately (Christensen and Overdorf, 2000). Prior literature has established the difficulty established firms have encountered when systemic change occurs, because rigidities in their existing processes are difficult to overcome (e.g. Christensen, 1993). In our study, we focus on the *technological* and *market* systems, as these systems are more easily studied than the *organizational* system, which is internal, not easily codified, and difficult to measure.

1.1.3 Systemic Change's Effects on a Firm's Technological Boundaries

Prior literature has found multiple explanations for firms' production boundary choices. The TCE literature indicates that firms should make production boundary choices based on the governance mode that delivers the lowest sum of production and transaction costs (Williamson, 1985). It may cost more for an organization to govern an activity in the market than it costs for a firm to manage the activity internally. This may be because the production activity is difficult to monitor when performed outside the firm, creating severe challenges for adaptation when costs or performance outcomes diverge from expectations. When it is difficult for a firm to make and enforce contracts, such as when the environment is uncertain, the activity is more likely to be moved within firm boundaries (Holstrom, 1999; Williamson, 1981, 1985, 1991). When technological change occurs, firms may have different knowledge than their suppliers do, which can increase coordination costs between the firm and its supplier as specifications are modified (Conner and Prahalad, 1996). Firms that move production in-house may want additional power over their activities, in order to increase managerial control over outcomes and to decrease uncertainty and improve firm performance (Thompson, 1967; Pfeffer and Salancik, 1978).

Systemic technological change can alter the efficiency and effectiveness of a particular boundary choice, and the boundary choices made at a point in time can affect a firm's ability to adapt to subsequent systemic change. The literature does not make clear what configuration of boundaries is most advantageous for adapting to this type of technological change. With continuously changing technologies, contracts pertaining to components may be necessarily incomplete, which would encourage broader production boundaries as firms integrate to avoid transaction costs (Kapoor and Adner, 2012). Firms that produce more components in-house might respond faster to technological change if they can develop the skills needed to incorporate the new technology into existing systems faster internally than these integrative skills can be accessed through the market (Negro and Sorenson, 2006; Sorenson, 2003). On the other hand, when component technologies are evolving, it may be preferable for firms to maintain narrow production boundaries until major technological uncertainties are resolved. Firms that maintain broad boundaries accumulate more assets and knowledge of components and interactions that could become obsolete with new technology, increasing the difficulty and cost of adjusting capabilities to the new technology. By contrast, firms with narrow production boundaries would be free of obsolete manufacturing assets, and also have the ability to switch between suppliers as they try out variants of an emerging technology (Balakrishnan and Wernerfelt, 1986; Adner and Kapoor, 2010; Afuah, 2001).

An implicit assumption in some of this work is that when technologies change, firms can easily test out the new technologies before committing to them. This implies that an open standard exists, which enables new component or manufacturing technologies to be dropped into the existing system with minimal change to other parts of the technology system. An open standard would enable firms to easily incorporate components from suppliers and create a functional device. However, it is often the case that a change in one component disrupts other parts of the product and/or manufacturing system (Henderson and Clark, 1990; Christensen, 1992). It is unclear from the previous literature, whether broad or narrow production boundaries enable adaptation to systemic changes and how the breadth of knowledge boundaries affects a firm's abilities to adapt. What constitutes an efficient governance mode for changes in the production of individual components may not necessarily be efficient for changes in the technological system (Hoetker, 2005; Kapoor and Adner, 2012). In particular, technological progress in one component may alter what is needed from other components within a device, forcing firms to make architectural changes in order to improve overall device performance (Funk, 2009; Rosenberg, 1976). If the affected components are outsourced, a firm could find these changes difficult to incorporate as its suppliers would need to adapt the components in unanticipated ways. These difficult-to-predict systemic outcomes make it challenging for firms to tailor individual transaction decisions to adapt successfully to systemic change (Brusoni et al., 2001; Rosenberg, 1976).

1.1.4 Systemic Change's Effects on a Firm's Market Boundaries

A firm's market knowledge boundaries can be extended by participating in multiple product and geographic markets and might increase a firm's likelihood of surviving systemic change if it enables a firm to find and exploit a new market opportunity quickly (e.g. Gavetti, Levinthal, Rivkin, 2005; Zhou and Li, 2012; Tripsas and Gavetti, 2000). Taylor and Greve (2006) and

Chesbrough (2003) found that firms with broader knowledge bases were better able to innovate and better able to find market opportunities for their new innovations. This market knowledge can aid a firm's efforts to commercialize products that address these new market demands (Christensen 1993, 1997; Rothaermel, 2001, 2005). Zhou and Li (2012) found that firms were better able to innovate radically when they possessed a broad market knowledge base.

Because systemic change creates new markets, it also affects a firm's market production boundaries, or a firm's method of commercializing its technological products (Christensen, 1993). Authors (e.g. Rothaermel, 2001, 2005; Tripsas, 1997) have acknowledged the importance of a firm's market production boundaries (consisting of in-house sales networks, marketing teams and investments in distribution channels) for the successful commercialization of new technology. Tripsas (1997) and Rothaermel (2001) showed that firms with relevant complementary assets, including downstream marketing and sales and distribution capabilities, were more successful after a technological change. On the other hand, older marketing and distribution assets can create information asymmetries that make a firm less likely to invest in a new market, and less likely to address the needs of a new customer base (Christensen and Rosenbloom, 1995). Thus, these complementary assets (and their accompanying capabilities) may no longer be useful for commercializing this new technology in these new market spaces. Appendix C contains a table with a literature review on market and technology knowledge and production boundaries.

1.1.5 Adaptation through Knowledge and Production Boundaries

Acknowledging the challenge that systemic change presents, more recent work has adopted a knowledge-based perspective to consider how what firms know, in contrast to what they make, affects their success in adapting to technological change (Brusoni et al., 2001; Kapoor and Adner, 2012). Firms with broader knowledge boundaries may be better able to recognize new market opportunities and to redesign products with new component configurations to address the new customer requirements created by systemic change (Brusoni et al., 2001; Chesbrough, 2003; Takeishi, 2002; Zhou and Li, 2012). This, in turn, would allow firms with broader production boundaries to incorporate technological changes into a product and bring the new technology to market more quickly (Negro and Sorenson, 2006). Kapoor and Adner (2012) found that firms with broad production boundaries had a faster time-to-market than firms with narrow production boundaries. However, they also found that firms with narrow production boundaries had performance benefits when they also had broad knowledge boundaries on outsourced components. Together, these works indicate the importance of considering a firm's knowledge and production boundary choices together, as both can affect a firm's survival prospects and capabilities for addressing systemic changes. But it is unclear from the existing literature when firms are best served by maintaining broad knowledge boundaries, when they also need broad production boundaries, and when they should retain breadth in only one of these domains.

In this study, we consider the effects that broad technology and market production and knowledge boundaries have on firms' abilities to adapt to systemic change that affects a firm's technological and market systems. A firm's *technology knowledge boundaries* are defined by the technology domains in which it has research and/or design experience (e.g. as described by patent classes) and thus understands sufficiently to employ in the design of new products or processes. A firm's *technology production boundaries* are defined by the component technologies in which it has manufacturing experience and thus understands sufficiently to convert designs into tangible devices. We distinguish firms that have broad technology production boundaries (if they manufacture component technologies) from those with narrow boundaries (if they do not manufacture component technologies), and measure technology knowledge boundary breadth as the number of component subclasses in which a firm has patented. A firm's *market knowledge boundaries* are defined by the types of customers or customer needs it understands (e.g. as indicated by its participation in different product markets or market segments). A firm's *market production boundaries* are defined by its experience with the activities used to deliver manufactured products. We distinguish firms that have broad market production boundaries because they have integrated into marketing and distribution activities from those with narrow boundaries in this respect, and measure market knowledge boundary breadth as the number of product markets in which a firm has participated.

Our study builds on Kapoor and Adner (2012) and differs in several important ways. While Kapoor and Adner focus on technological boundaries sustaining product innovation, we study the influence of firm boundaries on survival in a context that was frequently punctuated by systemic change and in which systemic changes often brought about a disruption to the established market systems. Specifically, several systemic changes led to product offerings that included new features but did not initially meet the performance criteria established by previous technology and required by the then dominant customers, but which ultimately dominated the largest markets for the technology. Accordingly, we also focus on how firms' market boundaries affected their survival prospects. An interesting feature of our context is that there were frequent shifts between open and closed standards. As new component technologies were introduced, they disrupted established technological systems and firms developed proprietary product architectures to incorporate them. However, through reverse engineering and other forms of vicarious learning, the new component technologies eventually diffused, suppliers of the new components emerged, and the industry settled back into a more open architecture. Periods of stability and the advantages from designing and developing and particular technology were short lived, though. With frequent systemic change, firms need the capability to adapt their technological and market systems in unanticipated ways, yet existing literature provides limited insight into how a firm's knowledge and production boundaries can best position them for this kind of turbulence.

2.0 HYPOTHESES

2.1 TECHNOLOGY KNOWLEDGE AND PRODUCTION BOUNDARIES

As outlined above, systemic change disrupts a firm's technological and market systems, creating new markets and requiring new combinations of technical knowledge and skills to respond to customer requirements (Christensen, 1993; Henderson, 1990). We expect broad technology knowledge boundaries to increase a firm's likelihood to survive such systemic technological changes for two reasons. First, experience in multiple technology domains broadens a firm's absorptive capacity, increasing the likelihood that at least some of what it knows will help it to understand a new component technology and anticipate how to adapt other components to leverage its advantages (Cohen and Levinthal, 1990). Firms with broad technological knowledge can recombine existing component knowledge in new ways to accommodate systemic disruptions to the technological system (Hargadon and Sutton, 1997; Fleming, Mingo, and Chen, 2007). Second, broad technology knowledge boundaries, attained through experimentation with many different components and their interactions (Brusoni et al., 2001; Takeishi, 2002; Yayavaram and Ahuja, 2008; Zander, 1995), also provide a firm with coupling knowledge. This enables a firm to know which components can be combined and how they will interact and perform at different parameter values (Brusoni et al., 2001; Takeishi, 2002; Yayavaram, 2008; Zander and Kogut, 1995), which, in turn, can increase the speed with which the firm can incorporate new components into a device (Fleming and Sorenson, 2001; Takeishi, 2002).

Thus, firms that have broader technology knowledge boundaries may be better equipped to adapt to a systemic technological change as they are better able to predict the effects of a new component on the overall device, and to incorporate the new technology more quickly. Firms with broad technology knowledge boundaries have greater insight into different potential couplings of new component technologies that, in turn, should increase their likelihood of survival through a systemic change. In line with these arguments, we propose:

H1: Technology knowledge breadth will delay a firm's exit from a market.

In addition to requiring new combinations of technological knowledge and skills, systemic change may also shift manufacturing processes and specifications. The systemic change may require new materials to be used and factories to change processes to incorporate the technological change within the component. Firms that integrated their manufacturing, and thus have broad technology production boundaries, might be able to respond more quickly to systemic change by working through the experimentation needed to assimilate a new component technology and adapt multiple component interfaces internally. A firm that controls the production of several component technologies and the multiple associated manufacturing technologies is more likely to move down the learning curve faster than an individual component supplier when system level knowledge is required to create a new product (Adner and Kapoor, 2010; Kapoor and Adner, 2011; Negro and Sorenson, 2006; Sorenson, 2003). Contracts tend to be incomplete when the parameters of the technology cannot yet be specified to the supplier and the product architecture is unstable. Firms that are integrated into manufacturing would not be subject to potentially overpriced components from external suppliers or be forced to compete with other firms for supplier contracts, which could further slow adaptation (Arrow, 1975).

If the supplier of a component does not envision the same value from the new technology, it will be more difficult to work through the performance trade-offs and adjustments to the existing technological system. Both the focal firm and its suppliers may have trouble predicting design parameters that will maximize the device's performance. In such an uncertain situation, external suppliers could choose not to supply the new technology, or they could adopt an alternative technology that is not compatible with the focal firm's product design and performance goals (Negro and Sorenson, 2006; Sorenson, 2003), making it difficult to meet the customer needs and requirements of the emerging market. In contrast, firms that integrated into manufacturing have better control over the quality and specifications of their internal supplies as they choose the materials, the manufacturing processes, and the parameters.

In sum, firms that have broad technology production boundaries are better able to engage in the experimentation needed to adapt to systemic change and are able to respond quickly. A quicker response to a systemic change to a firm's technological system allows a firm to capitalize on new market opportunities and avoid ceding market share to new entrants (Christensen, 1993). We therefore propose:

H2: Broad technology production boundaries will delay a firm's exit from a market.

Beyond these main effects, we also argue that technology knowledge and production boundary breadth further interact with each other in their influence on firm survival during systemic changes. The reason for this interactive effect is that it may be difficult for either the R&D or the manufacturing function unilaterally to predict component interactions and to solve device performance issues. The firm would have difficulty forecasting changes in parameters, manufacturing processes, and materials to suppliers that must take time to learn the new technology. If the product must be brought to market quickly, and interactions with new components are unknown and systemically affect device performance, firms must have a close working relationship between R&D and manufacturing, to enable collaborative problem solving (Hoetker, 2005) and a faster time to market. Firms that have both manufacturing and broad R&D within their firm boundaries would be better able to communicate information between these groups and jointly solve problems after a systemic change (Balachandra, 2002; Hoetker, 2005), thereby increasing the likelihood of quickly incorporating technological changes into products. Formally:

H3: Firms with broad technology production boundaries and broad technology knowledge boundaries will exit more slowly than firms that have narrow technology production boundaries and/or narrow technology knowledge boundaries.

2.2 MARKET KNOWLEDGE AND PRODUCTION BOUNDARIES

Systemic change can create new market opportunities for commercialization, with new customer bases and corresponding needs/requirements but to exploit these opportunities a firm might need to adapt its market system, or how it commercializes technology and profits from it. These new market opportunities generally begin as small niche markets that do not seem viable to large incumbents, and they may be particularly difficult for incumbents with narrow market boundaries to recognize or appraise (Christensen, 1993).

Firms with broad market knowledge boundaries come to understand a wide range of customer needs and preferences and how to satisfy them and thus may be capable of acting quickly to exploit new market niches created by systemic change (Chesbrough, 2003; Zhou and Li, 2012). One method of achieving broad market knowledge boundaries is a firm's exposure to different markets through diverse product offerings. Previous studies have found that product diversification enhanced firm performance (e.g. Tallman and Li, 1996; Barkema and Vermeulen, 1998) and have theorized that product diversity gives firms a richer knowledge base through exposure to new ideas and routines that, in turn, increase the firms' technological capabilities (Abrahamson & Fombrun, 1994; Miller & Chen, 1994, 1996). Participating in multiple product markets helps firms to understand a wide variety of the applications customers are using products for, and to better anticipate emerging market opportunities and capitalize on them. Broad market experience provides analogues that can be used to anticipate the growth trajectory for new markets (Gavetti, Levinthal, and Rivkin, 2005).

By contrast, a firm with narrow product offerings can suffer from cognitive inertia, which can keep it focused on its existing customer base, and prevent it from creating new products and finding new markets for commercializing new innovations (Tripsas and Gavetti, 2000). A firm with diverse product offerings is better able to overcome organizational inertia that focuses a firm's attention on current markets and customers, allowing it to seek out new market opportunities for new technology commercialization (Ahuja and Lampert, 2001; Zhou and Li, 2012), created by systemic change. In addition, as they seek and seize new market opportunities for their inventions, firms with broad market knowledge generate more unique recombinations of knowledge to draw upon (Ahuja and Katila, 2001) and thereby more flexible routines (Feldman and Pentland, 2003; Sorenson, Cohen, Roy, and Ren, 2006) that can be adjusted to cope with change.

As a result, firms that have more experience competing in different markets are more likely to survive a systemic change, since it gives the firm greater knowledge breadth and reduces a firm's myopia regarding existing market segments. Firms with broad market knowledge boundaries are better able to identify and accurately evaluate a new market's potential. In line with these arguments, we therefore propose:

H4: Market knowledge breadth will delay a firm's exit from a market.

Firms that come into the industry with a particular technology will gain knowledge about the corresponding customer base and performance requirements for that technology through investments in downstream assets, such as a marketing and sales department and different distribution channels. Firms that invest in more of these activities have broader market production boundaries (Christensen, 1993, 1997). When systemic change creates new markets, these may require new distribution channels and sales and marketing approaches. A firm's existing market production boundaries, it way of marketing and distributing its technology products for profit, can make adapting to new downstream activities challenging.

Before a systemic change, when technologies and markets are relatively stable, a firm that has invested in downstream assets (i.e. marketing teams, distribution channels, sales networks, etc.) is more likely to survive (Rothaermel, 2001, 2005; Tripsas, 1997) because the enhanced customer knowledge from their broad market production boundary likely leads to increased cash flow from its current customers. If a systemic change creates new markets for which those downstream assets and capabilities are no longer relevant, the firm is unlikely to receive correct information from current customers about the size and potential of the new market as well as the new customers' needs, (Harrigan, 1985; Christensen, 1993). Firms with market-specific downstream assets have information filters that are focused on existing customers' feedback, but may not be able to see a new customer base and understand its different needs and performance requirements.

Complementary downstream assets also raise the adjustment costs firms incur to transition away from their initial markets and from performance metrics valuable to customers in those markets because resources have already been committed to serve the old customer base. In other words, the firm is "locked in" by investments in customer data and distribution channels for the old customer base, which are no longer relevant for the new market. Saddled with higher adjustment costs, any new market must be large enough to justify the additional expense of the new complementary assets necessary to succeed in the new market and the potential desertion of the old complementary assets. Most new markets start off very small, however, which does not justify the adjustment cost for firms to move away from their old customers and target a new market segment, thereby making them less likely to adapt to a systemic change (Christensen, 1993, 1997, 1998). We therefore propose:

H5: Broad market production boundaries will accelerate a firm's exit from a market.

Although broad market production boundaries (i.e. being heavily vertically integrated downstream from manufacturing, for each market that a firm participates in) can slow adaptation to systemic change, the effects may be attenuated somewhat if the firm also participates in many different product markets, providing it with broad market knowledge boundaries. Firms with broad market knowledge boundaries may be aware of new technology and emerging markets

(Laursen and Salter, 2006; Zhou and Li, 2012), increasing the chances that it recognizes the new market and can appropriately appraise its potential value. We therefore hypothesize that:

H6: Firms with broad market production and broad market knowledge boundaries will exit more slowly than firms with broad market production and narrow market knowledge boundaries and firms with narrow market production boundaries.

3.0 METHODS

3.1 INDUSTRY CONTEXT

The context for our study is the hard disk drive (HDD) industry, which we follow from 1975 through 1999. Prior research on this industry has generally concluded prior to 1999 since the Hard Disk Drive Trend Report, a major source of company and product data ends at this point (Barnett, 2004; Hoetker, 2007). This industry provides an ideal setting in which to evaluate the effects of firms' knowledge and production boundary breadth on their survival through change, for several reasons. First, from its genesis, the industry has experienced multiple systemic technological changes within a short time period (Christensen, 1993, 1997) (see Figure 2 for a chronology of the different changes that occurred in the industry during the period of study). Second, products were complex, consisting of multiple components that each progressed at different rates technologically (Christensen 1993, 1997). This type of technology is characterized by frequent systemic change because, in order to derive maximum benefit from substantive component innovations, firms need to alter other components and the architecture which links them (Rosenberg, 1976). Third, with each wave of systemic technological change the adaptive benefits of firm's boundary choices were tested, as product designs required modification and the technological standards governing how components could interface fluctuated between closed, proprietary and open standards.

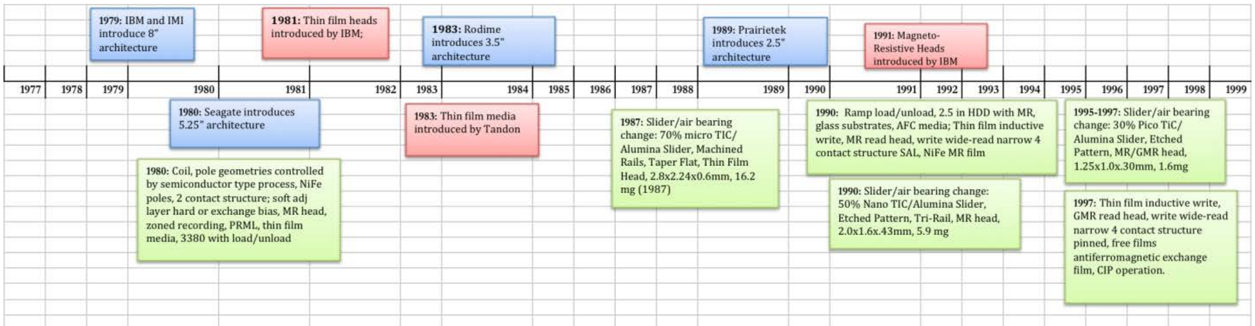


Figure 2. Chronology of Technological and Market Changes in the HDD Industry: 1977-2009

3.1.1 Manufacturing/Production of Disk Drives

IBM introduced the Winchester drive in 1973, a sealed HDD drive (Christensen 1993). Disk drives contained magnetically coated disks where data could be recorded, a head that read the data, and actuator that moved the head to the correct location on the disk and an interface with the computer. All components were enclosed in a sealed casing (Lerner, 1997). The first commercial drives were 14” in size and sold in mainframe computers or directly to computer users (Barnett 2004).

There are two major components in disk manufacturing: the read-write head and the disk. To manufacture disk media, both sides of a platter are coated with different materials. Different coatings have been used as technology improved (e.g. a change from iron oxide to thin-film), which enabled disks to hold more data in less space, be more durable, and be more reliable. The finish must be smooth without the imperfections that can cause the read/write head to crash, decreasing reliability and storage capacity. The original process for head manufacturing was winding copper wire around a ferrite core, but as technology progressed and materials (and their physical properties) changed, head manufacturing was modified. HDD manufacturers had to continuously invest in new capital equipment because of frequent technological changes. The HDD market was a cost competitive market, which required the HDD manufacturers to run large, global manufacturing operations to meet low price demands (Kumar, 2003). One of our interviewees stated that firms that did their own manufacturing could ensure a cleaner facility, would affect long-term reliability of their disk drives, a key driver of customer satisfaction (Interview 1, 1-18-13).

3.1.2 Firm Typology

Three different types of competitors were prevalent in the HDD industry: established firms, entrepreneurial start-ups and diversified firms. Fourteen firms were considered established firms in the industry (e.g. IBM, Burroughs, and Digital Equipment Corp, among others). These firms included computer manufacturers that made their own drives for their computer products. These firms tended to be vertically integrated as they had to produce all of the components necessary for the drives before component suppliers came into existence in the late 70s/early 80s. Another 103 firms were entrepreneurial startups (e.g. Seagate, Conner Peripherals, and Rodime, among others). Start-ups in this industry were usually backed by venture capital financing and focused only on the hard disk drive industry. These firms were usually involved in both the design and manufacture of hard disk drives. These firms did not make computers, but instead sold their drives to end-users (the PCM market) and to computer manufacturers (the OEM market). These firms rose to prominence as components became available from independent supplier firms.

Start-ups tended to enter the hard disk drive industry by using older generations of the component technologies, once they had been reverse engineered, or were being phased out by the technology leaders, and open standards for the technologies' interface with the rest of the drive had been established. Startups did not initially need to be vertically integrated, as they could obtain heads and media from suppliers, assemble the components, and sell the completed drive in the OEM market (Christensen, 1993).

Fifty-six firms were diversified firms (e.g. 3M, BASF, and Samsung, among others). These firms were involved in multiple industries, with disk drives as one of their product lines. These firms expanded into the hard disk drive industry to gain new market share, and in some cases adapted technology used in other markets for use in disk drive production (Christensen, 1993).

The industry became more global as it matured. Japanese firms entered the market seven years after the US (US firms: 126, Japanese firms: 36), Europe (27 firms) 12 years after, followed by Brazilian (10 firms), Taiwanese (4 firms), and Korean firms (6 firms) in the early to mid 1980s. As the market first emerged, most countries' HDD markets were domestic, with domestic computer manufacturers purchasing HDD from domestic HDD manufacturers, but firms soon began to market their drives globally (Barnett 2004).

3.1.3 Market Typology

There were three different markets for disk drives: Captive, PCM and OEM. Some firms competed in multiple markets at once, while others concentrated on a single market. Some firms (e.g. Data General, Digital Equipment Corporation, Hewlett-Packard and IBM, Control Data, and Hitachi, among others) manufactured "captive" disk drives for their own computer products.

Other firms, such as Century Data, Wangco, and Kennedy sold drives directly to computer users who needed additional data storage for their IBM computers. This PCM market thrived by imitating IBM's technology and offering less expensive storage than IBM (Christensen, 1992). In the mid-1970s, the minicomputer market developed, and hard disk drives were now sold directly to computer manufacturers and the OEM market emerged (Filson, 2004). Firms such as Memorex, Perkin-Elmer, and Storage Technology sold drives directly to computer manufacturers. The computer manufacturers frequently needed more drives in addition to their captive drives to keep up with demand for their computer products. But some computer manufacturers did not make their own captive drives and purchased them from other firms in the OEM market (Christensen, 1992).

3.1.4 Typology of Technological Changes in the Industry

Form factor changes were reductions to the size of the disk drive. Their smaller size meant the drives could be used with different types of computer products (e.g. desktops, laptops, notebooks, and handheld devices, among others) that appealed to different end users. Each new form factor initially attracted a small customer base with different needs than customers for the previous form factor. The early-adopting customers for the new form factors were willing to accept decreased reliability, speed and storage capacity in exchange for drive availability and lower prices. The technological leap to a new form factor was not large, since much of the same technological expertise was still relevant. Smaller drives meant that components had to shrink and sometimes be redesigned, which had unpredictable implications for the interfaces between components (Barnett, 2004). But the real challenge was for established firms to recognize the viability of the new market segment. Many established firms relied on their larger, older customers and did not recognize the opportunity in these new markets as lucrative, and were slow to bring the smaller drives to market. Profit margins were much smaller for the new form factors than for their older generation products. As one of our interviewees stated, reliability was "king" for established firms, because older products (like mainframes) that failed meant millions of dollars of damage (Interview 3, 1-25-13). It was difficult for established firms like IBM to offer products that did not meet their very low tolerances for failure and products developed for new markets tended to be less reliable, at least initially. New entrants (start-ups and diversified) focused on creating new form factors, and finding new markets (such as laptop computers) to sell them to. By the time the established firms recognized the importance of a new market and introduced a new product in that form factor to compete, the new entrants already had established economies of scale and the established firms could never regain market share from them (Christensen, 1993). Figure 3 presents a list of form factor introduction dates, along with the first firms to introduce each drive to the market.

14"- IBM, 1973
8"- IBM and International Memories,1979
5.25"- Seagate, 1980
3.5"- Rodime, 1983
2.5"- Prairietek, 1989

Source: Disk/Trend Report

Figure 3. Form Factor/Architecture Introduction Dates

In addition to smaller diameter drives to serve new markets, firms also had to innovate in more expensive component technology that improved areal density, speed/access time and reliability (Lerner, 1997). Component changes, such as those precipitated by the use of different materials, often required new manufacturing processes for the read/write head and the disk media and might also require changes to the electronics and other components. However, they tended not to drive changes in the market applications of hard disk drives, in the same way that form factor changes did. Component changes often took years of very expensive R&D, progressed at different rates, and created interaction problems with other components within the device, which caused device performance to suffer unless a firm knew what parameters to adjust and how to interface components together. These changes, most notably the magneto-resistive (MR) head, required multiple departments (R&D, product development, manufacturing, etc.) to work together to get the device to work with the new component (Interview 2, 1-23-13; Interview 3, 1-25-13)

It was also not always clear which technology would become dominant. Some firms made the wrong bets on technology and had to exit. For example, Ampex tried to commercialize the Alar film disk, but the disk was not mechanically robust or durable, which caused a high failure rate. Other firms waited too long to introduce new technology and were forced to exit. For example, Applied Magnetics waited too long to invest in thin film heads and then MR head technology and was forced to exit (Interview 1, 1-18-13).

Because of the frequent technological changes, slim margins, and short product life cycles, firms could not afford to miss two product cycles – doing so meant the firm would almost certainly have to exit the industry (Interview 1, 1-18-13). Thus, there was an incentive for rapid innovation because of quickly decreasing profitability over the short product life cycle (6-9 months). Most firms had trouble keeping up with the increases in storage capacity and the reduction in physical size of the drive (Barnett, 2004). Figure 4 lists important component change introduction dates, as well as the firms that first introduced the new components in their HDD products.

Thin Film Heads	1981	IBM
Thin Film Magnetic Media	1983	Tandon
Magneto Resistive Heads	1991	IBM

Source: Disk/Trend Report

Figure 4. Component Change Introduction Dates

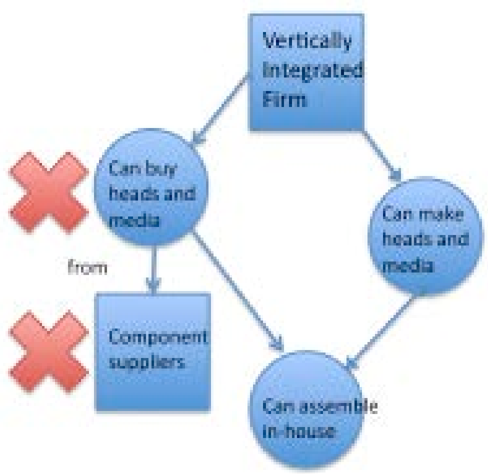
3.1.5 Vertical Integration into Technology Production in the HDD Industry

Vertical integration into production (manufacturing components) was capital intensive, and did not seem necessary to firms that had access to components from suppliers and could use these outsourced components to assemble their own drives (Christensen, 1993). This arrangement worked well when the technology was stable and the interface between components was known (open standards were established during periods of stability as firms learned the interface between a set of components). However, when technological change occurred, many suppliers ceased operation because they could not integrate the new technologies into their component products quickly enough (Interview 1, 1-18-13; Interview 2, 1-23-13). This put non-vertically integrated firms at a disadvantage, as they no longer had a supply of components that could be incorporated into the drives. Systemic technological change also created system integration problems for the non-integrated firm. Interactions between components changed (so standards were no longer open or known during periods of instability), so it became more difficult for firms to integrate new components into the device without having process (non-patented) knowledge about their properties and how each component interfaced with the others. Since there were frequent technological changes of this type within the industry and product life cycles were so short (6-9 months), firms needed to be able to manufacture and incorporate the component innovations into the device quickly, or they would lose market share on a product generation (according to our interviewees, two misses were fatal to a firm). These firms either had to vertically integrate, or exit the industry (Interview 1, 1-18-13).

Figures 5 and 6 visually represent the ramifications of boundary choices for systemic change in the HDD industry. Figure 5 presents the different boundary choices a firm had for drives, head and media components and drive assembly in a stable environment. In a stable environment, standards for components (e.g. materials, specifications and parameters for interface with other components within the device) were open and known by the firms in the industry. Thus, firms could make their own components, but also had the ability to buy components from suppliers since interactions/product architecture standards were open and known, and assembly did not require much system integration knowledge. Figure 6 presents the different boundary choices a firm had for drives, component supply and assembly after a systemic change. After a systemic change, standards for components were closed and not known by all the firms in the industry. Firms did not know how a new component material, for example, would affect the other components within the device, and did not know the specifications needed to maximize the drive's performance. In this situation, as represented by the Xs, firms had to make their own components, as suppliers were not able to stay in business when technological uncertainty increased and interactions/product architecture was unknown (Interview 2, 1-23-13).

Sources: Interviews 1, 2, and 3, Christensen (1993) and McKendrick (2000)

Figure 5. An HDD Firm's Vertical Boundary Choices in a Stable Environment



Sources: Interviews 1, 2, and 3, Christensen (1993) and McKendrick (2000)

Figure 6. An HDD Firm's Reduced Vertical Boundary Choices after Systemic Change

3.1.6 Vertical Integration into Market Production in the HDD Industry

Firms could choose to distribute their drives using internal marketing departments, or they could distribute their drives through an intermediary (as Hitachi did in Europe, partnering with BASF and Siemens) (data from Disk Trend Report). The large firms (e.g. IBM) had their own sales, marketing, and distribution staffs, but these staffs were geared towards large customers they could serve with proven technology with high margins (e.g. IBM's enterprise system business). The smaller firms picked up smaller volume contracts by using older technology, but not from large firms like IBM that were disinclined to sell their component technology in the OEM market or license it to other firms (Interview 3, 1-25-13). Many of the smaller firms did not have budgets that could support a marketing team, and relied on personal contacts within the industry for smaller scale customers that larger firms did not pay attention to because the sales contract volume was too small (Interview 3, 1-25-13). Many of the executives who worked in HDD from the beginning of the industry moved to different startups (see Christensen, 1993, who traces founders who moved amongst startups over the years), bringing their customers with them.

3.2 SOURCES

We constructed our dataset from four main sources: the National Bureau of Economic Research (NBER) patent database and the US Patent and Trademark Office (USPTO) patent databases for patent information; the Securities Data Corporation database (SDC) for alliance and M&A data; and the Hard Disk Drive Trend Report, an annual publication by Jim Porter from 1976-1999, that we used as a source for categorizing firms into strategic groups and for introduction dates for each of the firm's technologies, as well as for market share information, entry, exit, and founding dates, product diversity, competitors, industry market data, and marketing and technology production activities for each firm annually. We have also compiled company histories by year for each of the 228 firms in the industry using 1976-1999 from the Hard Disk Drive Trend Report, using SDC to corroborate information about firms' activities.

To trace each firm accurately over our 20 year time period, we consolidated companies and their resources based on the M&A data from SDC and Disk Trend Report and name changes from Disk Trend Report's manufacturer profiles. Over the time period, multiple firms merged assets (including knowledge resources such as patents), so we consequently had to account for this in the data. When a firm changed names, the two firms were consolidated in the data. If a firm purchased assets of another firm from a bankruptcy, we did not consolidate, because there was no way to know what specific resources were obtained through the asset sale. Finally, when firms merged or one firm acquired another, the assets of the two firms were consolidated together, to account for the knowledge resources accumulated by the M&A.

Finding data on firm's activities was challenging, as most of the firms within the population (120 firms, 72% of the population) were private, and had an average lifespan of 4.5 years. In addition, most of the public firms (e.g. BASF, Siemens, 3M, etc.) were large, diversified firms and did not have information available on the specific divisions that competed in HDD. Daily and Dollinger (1993) as well as Durand and Vargas (2003) have noted the challenges involved with obtaining data on the activities of small private firms. We had to rely on what was in Disk Trend Report, McKendrick (2000), other papers on HDD history (e.g.

Christensen, 1993; Barnett, 2004), and the expertise of our interviewees for the information we coded (similar to Ozcan and Eisenhardt, 2009).

In particular, as there was no direct source that listed a firm's knowledge or production activities within the industry, we relied on coding qualitative data from within the company histories for each firm, each year. Each company history chronicles each firm's experience in the industry to 1999 (or up to its exit is it occurred prior to 1999) and consists of two single-spaced pages on average.

We used the company histories and data from Disk Trend Report to code each of the variables we hypothesized would affect survival. *Technological production* boundaries were coded as 1 for broad and 0 for narrow based on qualitative evidence of manufacturing of components within the company histories (e.g. an excerpt from Disk Trend Report: "Disks will be internally produced using a hybrid plated/sputtering process, and a new production facility is planned for Austin, Texas"). The *breadth of technological knowledge* was measured using patent data from NBER and USPTO. However, many firms in the industry do not patent, so we also coded whether firms engaged in R&D activities using qualitative evidence provided in the company histories (e.g. an excerpt from Disk Trend Report: "Samsung maintains an R&D center for disk drive design in San Jose, California."). *Broad* (versus narrow) *market production* boundaries were similarly coded for firms based on qualitative evidence of marketing sales, and distribution activities within the company histories (e.g. an excerpt from Disk Trend Report: "ISS also has an OEM marketing program, carried out with moderate success to date, but which will probably grow."). *Breadth of market knowledge* was measured as a count of the different product groups each firm offered products in, each year. See Table 1 below for examples of how we used the qualitative data to code these variables:

Table 1. Examples of Qualitative Data Coded for Main Effects

Boundary	Source 1	Source 2
Market production	"The least vertically integrated is Quantum, which for the most part handles only design and marketing, leaving all assembly to its Japanese partner MKE." (source: McKendrick, 2000)	"In 1991, Quantum further strengthened its efforts to increase sales through distribution, folding Plus Development and its industrial distribution activities into a business unit named Quantum Commercial Products. Quantum also operated a direct marketing subsidiary, LaCie Ltd., which has been attached to the new business unit. About 30% of Quantum's revenue comes from distribution. (source: Disk Trend Report, 1991)
Technology knowledge	"Samsung maintains an R&D center for disk drive design in San Jose, California." (source: Disk Trend Report, 1991)	"Samsung has R&D facilities in South Korea and California." (source: McKendrick, 2000)
Technology production	"The company has an extensive geographic reach. Its operations outside the US include manufacturing facilities in Malaysia, Singapore, and Thailand as well as sales offices throughout the Americas, Asia Pacific, Europe and the Middle East." (source- Western Digital SWOT analysis on Business Source Complete)	"Western Digital had manufacturing operations in Singapore as of 1988." (source-McKendrick, 2000)

The interviews (see Appendix A) enabled us to fill in gaps in the data we needed to construct the main independent variables described below, and it was helpful in interpreting what the measures could capture as well as the patterns we observed. The former CTO of one of the surviving firms provided contacts and introductions to key managers at firms in the industry. In particular, these interviews provided insight into the kinds of technological changes that the HDD industry experienced, which required systemic change to a firm's technology and/or market systems, and how firms dealt with systemic technological change.

3.3 DEPENDENT VARIABLE

The primary dependent variable for our hypotheses is firm survival. We used a binary indicator of whether a firm survived during the period of study. We defined a firm as having exited when a firm no longer shipped products in the HDD industry, either because of bankruptcy (48 firms), M&A (42 firms, that after the M&A, were no longer making HDD products), or divestment (81 firms out of the industry) (Lexis Nexus, Disk Trend Report).

3.4 INDEPENDENT VARIABLES

We measured the *breadth of technology knowledge boundaries* with a continuous variable to indicate how many subclasses a firm patented in within the HDD industry (please see Appendix B for some examples of the subclasses used to define HDD and how they map onto specific components). We used the NBER/USPTO patent databases to obtain data on patent activity for each firm: which HDD firms patented and patent dates for 3 main classes: 360, 369, 428 (similar to Audia and Goncalo, 2007). Since our interviewees indicated that firms may have done R&D but may not have patented (either because they did not want their competitors to know what they were working on or because firms did not patent process technologies which are harder to protect with patents), we used information obtained through company histories and through interviews with industry experts to code a binary variable for firms that had been doing R&D (84 firms, 51% of sample) (Interview 1, 1-18-13; Interview 2, 1-23-13; Interview 3, 1-25-13). We added this to the continuous variable that counted patent subclasses for each firm in order to account for the process knowledge the firms could obtain through R&D.

We measured whether a *firm's knowledge production boundaries* are broad or narrow with a dichotomous variable of 1 or 0 indicating whether the firm manufactured major components (1, broad) or not (0, narrow). To obtain data on what manufacturing activities each firm performs each year, we used the company histories we compiled from the Hard Disk Drive Trend Report as well as McKendrick's (2000) lists of component manufacturers. An example of data found for a firm who manufactured components, from Disk Trend Report: "Cybernex, the previous thin film head manufacturer, evolved into Century Data, Inc., combining the operations of Century Data Systems, Cybernex Advanced Storage Technology (CAST), Amcodyne, Tecstor, and Ford-Higgins, a subsystem producer." When these data did not clearly indicate whether a particular firm manufactured its own components, we relied on our interviewees for guidance on which firms had manufactured and which firms had outsourced, and corroborated their information with Christensen (1993). The interviewees stated that the firms with the largest market share were the firms that were vertically integrated into manufacturing activities (with the exception of Seagate and Western Digital, that vertically integrated into manufacturing activities later. Seagate vertically integrated into manufacturing with the acquisition of the Imprimis division of Control Data in October, 1989 (verified by interviewees, SDC, and Disk Trend Report). Western Digital vertically integrated into manufacturing in 1995 with a factory in Singapore. Thus, we used the market share data from Disk Trend Report to code additional manufacturing data (125 firms, 76% of the sample, had data for at least one firm year, while 40 firms, 24% of the sample, had no data for any firm years). If data did not clearly indicate whether a firm manufactured components, and the firm was not listed in the top 20 rankings for firm market share (US or global) for that year, we used "0" to indicate that the firm did not do its own manufacturing. If data did not clearly indicate whether a firm manufactured components, and the firm was listed in the top 20 rankings for firm market share (US or global) for that year, we used "1" to indicate that the firm did its own manufacturing.

To measure a firm's market production boundaries, we used a dichotomous variable of 1 or 0 to indicate whether a firm directly sold, marketed, or distributed its products. This marketing data was obtained from the company histories we compiled from Disk Trend Report. When these data did not clearly indicate whether a particular firm marketed or distributed its own products, we relied on our interviews (see Appendix A) for guidance on which firms had done their own marketing and which firms had outsourced. Drawing from the interview notes (Interview 3, 1-25-13) and Christensen, 1993, the established firms were the firms that were vertically integrated into marketing activities, while startups lacked the capital to have large marketing teams, and looked to personal connections with computer companies to obtain business. We categorized each firm as a startup (103 firms in the sample), established computer firm (14 firms in the sample), or a subsidiary of a diversified firm (56 firms in the sample). To categorize a firm as an established firm, we used Christensen's lists of computer manufacturers that made their own drives, and a top 10 original industry disk drive manufacturer list by market share (Christensen, 1993). Although the market share list fluctuates over time, the purpose of this list is to show the established firms at the beginning of the study. The 18 firms listed in Figure 7 are the established firms in our sample.

Top 10 Disk Drive Manufacturers by Market Share
1. CDC
2. Diablo
3. Century
4. Pertec
5. Memorex
6. ISS/Univac
7. Perk Elmer
8. Data 100
9. Ampex
10. Microdata

Computer Manufacturers Who Manufactured Own Drives
1. IBM
2. Digital Equipment
3. Control Data
4. Data General
5. Burroughs
6. Fujitsu
7. Hitachi
8. Univac

Figure 7. Lists of Established Firms at Beginning of Study, 1976

To distinguish between a subsidiary of a diversified firm and an entrepreneurial startup, we used company histories to determine when firms were founded and what industries they were involved in. If a firm was involved in multiple industries, we labeled it a diversified firm, but if the firm was only in the HDD industry at its founding, we labeled the firm a startup.

If data did not clearly indicate whether a firm marketed or distributed its own products (70 firms, 42% of sample had data for at least one firm year, while 95 firms, 58% of the sample had no data for any firm years), and the firm was an established firm, we used “1” to indicate that the firm did its own marketing, if the firm was categorized as a “startup” firm, we used “0” to indicate that the firm did not do its own marketing, if the firm was categorized as a diversified firm’s marketing activities, we coded the data as missing (based on prior literature and our interviews, there was no basis to label diversified firms as integrated or not).

To measure the *breadth* of a firm’s *market knowledge boundaries*, we created a variable to account for the diversity of products each firm offered. This measure shows the diversity of products a firm offered in the HDD industry (and thus the number of product markets the firm was exposed to within the HDD industry). We counted the number of product groups each firm competed in annually (from the Hard Disk Drive Trend Report), similar to Carroll (2004).

3.5 CONTROLS

Competitor density: In the population ecology literature, *competitor density* has been shown to have a non-monotonic effect on firm survival (e.g. Hannan, 1989). To control for the effects of competitor density, we calculated the number of competitors for each firm for each year by product group and divided the number of competitors by the number of product groups each firm was competing in, using data from the Hard Disk Drive Trend Report in a similar manner to Carroll (2004).

Market size of industry: To control for macroeconomic effects that may have affected the industry due to its changing size and the influx of new entrants as new computer product markets became lucrative (see Christensen, 1993), we used Disk Trend Report to obtain the total dollar value of shipments in the industry for each year of study (in millions).

Market size by competitive group[3]: Shipments in the annual Disk Trend Report were grouped according to storage capacity and type of drive. If a firm was competing in fewer product groups or categories that were no longer financially rewarding, a firm may be more likely to fail. We used Disk Trend Report to obtain the dollar value of shipments in each competitive group for each year of study (in millions) in order to control for the amount of industry dollars each firm was directly competing for, which shifted by year.

[3] We used the squared value of this continuous variable in all of our survival models for better model fit.

Era dummy: Our interviewees stated that the biggest technological adaptive challenge occurred in 1991, when IBM introduced the magneto-resistive head (Interview 1, 1-18-13; Interview 2, 1-23-13; Interview 3, 1-25-13). We wanted to control for this specific change, as our interviewees stated that it was one of the most difficult to incorporate, required multiple departments to work together to solve interface/performance issues, and subsequently caused many firms to fail. We used a dichotomous variable with a value of 0 before the change took place in 1991, and 1 after the change occurred.

We tried to control for other firm characteristics such as size and age, to better distinguish the boundary effects that we predict from the firm characteristics we used to infer and assign the production boundary measures. The controls we tested included the alliance count per firm per year (as a proxy for firm size) and firm age at entry. We found that the models were robust to these additional controls, but the model fit and stability was better without them.

4.0 ANALYSIS AND RESULTS

We test our hypotheses with survival analyses, with the hazard rate defined as the probability that a firm exits the market in a moment t given that it has survived until this period and conditional on a vector of x_{it}, which may both include both time-varying and time-constant variables, where T is a non-negative random variable (duration), which we assume continuous, so that λ(t) is an instantaneous rate of exit (Kalbfleisch and Prentice, 1980):

$$\lambda(t; x_{it}) = \lim_{dt \to 0} \frac{\Pr(t \leq T < t + dt \setminus T \geq t, x_{it})}{dt}$$

We used the Accelerated Failure Time ("AFT") model to predict firm survival because results, reported as factors that will either accelerate or decelerate a firm's exit, are more intuitive and easier to interpret. The acceleration factors calculated by the AFT model allow us to evaluate the effect of each predictor variables on the survival time. Coefficients that are less than one indicate that the variable decelerates exit while coefficients estimated to be greater than one indicate the variable accelerates exit. Survival times follow a parametric lognormal distribution. (Collett, 2003; Dätwyler and Stucki, 2011; Swindell, 2009):

$$\log T_i = \mu + \beta_1 x_{1i} + \ldots + \beta_p x_{pi} + \sigma \varepsilon_i$$

We ran the models with robust error variances, which account for lack of independence between observations from the same firm (the Huber-White sandwich estimator of error variances). Table 2 reports basic statistics for each of the main effects and controls, while the correlation table in Table 3 reports the correlations for the main effects and controls.

Table 2. Basic Statistics

Variable*	Mean	Std. Dev.	Min	Max
Breadth of technological knowledge[4]	4.319843	13.78161	0	167
Broad technological production	.5626632	.4963819	0	1
Breadth of market knowledge	1.804707	3.149766	0	9
Broad market production	.5678851	.4956938	0	1
Average number of competitors	6.08895	11.71315	0	50
Industry size	14158.34	8245.945	2813.4	31736
Era dummy	.1501305	.3574327	0	1
Market size by competitive group	5279.375	6914.752	0	31162.2
Broad tech knowledge, Broad tech production (Matrix 1)	.4804178	.4999428	0	1
Broad tech knowledge, Narrow tech production (Matrix 1)	.1292428	.3356877	0	1
Narrow tech knowledge, Broad tech production (Matrix 1)	.0822454	.2749178	0	1
Broad market knowledge, Broad market production (Matrix 2)	.4921671	.5002653	0	1
Broad market knowledge, Narrow market production (Matrix 2)	.2898172	.4539738	0	1
Narrow market knowledge, Broad market production (Matrix 2)	.2362924	.4250814	0	1

*The number of observations for each variable was 766.

[4] The maximum value of 167 is an outlier. Over the period of study, there were only 26 instances where firms had technology knowledge over 100. The five firms with values over 100 were large diversified firms such as Sony and 3M.

Table 3. Simple Correlations for Main Effects and Controls

		1	2	3	4	5	6	7
1	Industry size							
2	Market size by competitive group	0.6193***						
3	Average Number of Competitors	0.0849*	0.1903***					
4	Era dummy	0.6043***	0.4808***	-0.1368***				
5	Broad tech production	0.0681+	0.3738***	0.1277**	0.0169			
6	Breadth of tech knowledge	0.2352***	0.4424***	0.0219	0.2593***	0.2217***		
7	Broad marketing production	0.0831+	0.2529***	0.0491	0.0715*	0.4369***	0.1804***	
8	Breadth of market knowledge	0.1280**	0.6461***	0.1807***	0.1496***	0.4858***	0.3229***	0.3283***

n=766, $^{***}p$= < .001, $^{**}p$ < .01, $^{*}p$ <. 05, ^{+}p < .10

Table 4 reports the estimates for the control variables in Model 1[5]. In Models 2 and 3 (see Table 4), we separately test for the individual effects of technology and market knowledge and production boundaries on firm survival.

Hypotheses 1 and 2 proposed that breadth of technology knowledge and broad technology production boundaries would positively affect firm survival. The coefficient for technology knowledge breadth is not significant (coefficient=.024, *p* =.112), and thus does not

[5] We did robustness testing with additional controls that could potentially affect survival, including percent change in US GDP (to account for changes in the economy that could have increased or decreased demand for computers and HDD), number of US competitors per year (the largest market in HDD was the US, so a greater number of competitors based in the US could decrease survival prospects of firms based elsewhere), product performance (a firm's survival directly corresponds to how well its products perform), alliance count per firm per year (which indicates the degree that a firm expanded its boundaries through alliances, as these firms may get some of the same benefits as internal breadth but for a lesser cost). We found that the models were robust to these additional controls, but the model fit was better without them.

provide support for Hypothesis 1. This result may reflect inherent differences in the type of R&D firms had to engage in to be successful through systemic changes in the HDD industry. After a technological shift, much of the knowledge that was needed to get the drives to work was systems integration process knowledge. Firms had to engage in this type of process-related R&D, which was usually not patented because according to our interviewees, process patents were almost impossible to enforce. We tried to account for this in our measures by including R&D that was documented in Disk Trend Report but did not become patented, but much of the R&D firms engaged in was never made public and kept secret from competitors (Interviews 1, 2 and 3 in Appendix A). There were patents granted in this industry, but many were granted to multiproduct firms that were involved in more than one industry with related technology, making it even more important for the firm to have patents to protect this knowledge. For example, one interviewee stated that MR head technology was patented by their firm many years before it was used in HDD so IBM could use it to compete in other arenas: “Early MR heads were used for magnetic stripe cards at Macy’s to read price tags just like credit cards, sensing magnetic bubbles, tape drives much earlier. IBM made these- so very broad R&D and product placement.” The patented technology then sat on a shelf until it was needed to solve a problem in another industry: “That’s when you would use your broad R&D to decide what to use to give you the transfer rate, capacity and reliability demanded.” (Interview 2, 1/23/13). Thus, firms with broad technological knowledge might have exited the industry at a higher rate, even if they had the capability to adapt, because their broad technological knowledge gave them other options.

The coefficient for broad technology production boundaries is .701 ($p < .10$), providing marginal support for Hypotheses 2. The coefficients in the AFT model indicate whether the effect of a unit change in the covariate is to accelerate (a negative coefficient) or delay (a positive coefficient) the time to failure. The lognormal AFT estimation assumes a linear relationship between the log of survival time T and firm characteristics, such that ln(T) = XB + e, where the error term is distributed loglinearly. Thus, one unit increase in X_i leads to a B_i increase in logged survival time. Alternatively, the exponentiated coefficients or time ratio, e^{Bi} , tells the increase (for values >=1) or decrease (for values <1) in survival time relative to a baseline scenario. This means that, using exp(.701), one standard deviation increase in technology production boundaries delays exit by 102%. This result supports prior literature, which has found that technological change requires close coordination between firms and their suppliers (e.g. Helfat and Campo-Rembado, 2010; Hoetker, 2005; Kapoor and Adner, 2012). It also supports our contention that systemic change is better handled in firms that are vertically integrated into the manufacturing function, enabling close coordination between manufacturing and design functions.

Hypothesis 4 proposed a positive relationship between market knowledge breadth and firm survival. The coefficient of market knowledge breadth, measured by a firm's product diversity, is .033 ($p < .10$), providing marginal support for Hypothesis 4. This means that, using exp(.033), one standard deviation increase in market knowledge boundaries delays exit by 3.4%. This finding could also be explained by more diversified revenue streams: firms had their revenues spread over more products and product classes, ensuring a revenue stream even when one product was not doing well (e.g. Berkovitz and Mitchell, 2007). However, there is also an opportunity cost to diversified revenue streams; firms that allocate resources to one division are taking away resources from another. Because diversification has costs, firms still need to choose wisely when evaluating a possible expansion to their product line (Levinthal and Wu, 2010). But there is additional literature that has found that firms involved with more than one product line are better able to absorb and retain new knowledge (e.g. Shipilov, 2009), and, we argue, may build new capabilities that better enable multiproduct firms to adapt to systemic change. Our findings show an adaptive benefit to product diversity, which indicates to us that diverse revenue streams are not the only cost or benefit a firm receives from product diversity.

Hypothesis 5 proposed a negative relationship between broad market production boundaries and firm survival, which was not supported (coefficient=-.293, p=.341 when run with product diversity market knowledge). Although our understanding of the industry suggested that each new form factor required a somewhat different set of downstream assets, to distribute and market products, these assets may have been more generic than we supposed. Also, it was difficult for us to separate the effects of market production boundaries from other factors such as firm size and diversification, and getting around the limitations of our data is a task for follow-on research to tackle. Many of the firms that did have investments in complementary assets (such as marketing, distribution, and sales networks) were large, diversified firms (i.e. Hitachi, Fujitsu, and Memorex, among others), that may have been able to share those assets across the different industries they competed in, and likely had more cash-on-hand to make those investments. Many of the smaller firms, which only competed in HDD, did not have the resources to invest in these assets, and relied more on personal contacts to get sales contracts with customers.

Table 4. Survival Models

Variables	Model 1: Controls	Model 2: Controls+ Tech Knowledge and Production	Model 3: Controls + Mkt Knowledge and Production
Breadth of technological knowledge		0.023697 (0.014932)	
Broad technological production		0.700934^{+} (0.384763)	
Breadth of market knowledge			-0.033153^{+} (0.018263)
Broad market production			-0.293089 (0.307989)
Average Number of Competitors	-0.026075^{+} (0.013700)	-0.0278843^{+} (0.014873)	-0.001315 (0.010500)
Industry size	-0.000136 (0.000104)	-0.000122 (0.000092)	-0.000079 (0.000093)
Era dummy	-1.260642 (0.940431)	-1.017841 (0.851757)	-0.579638 (0.648131)
Market size by competitive group	0.000169^{+} (0.000095)	-0.000013 (0.000070)	0.000071 (0.000086)
Constant	3.277100*** (0.697995)	2.954313*** (0.578973)	2.795746*** (0.729270)
X^2	5.76	8.43	9.90
Log likelihood	-91.61655	-86.40719	-60.43027
AIC	195.2331	188.8144	136.8605

n=766, standard errors shown in parentheses, *** p= < .001, ** p < .01, * p <. 05, $^{+}$ p < .10

We used dichotomous variables to classify firms according to their mix of broad and narrow boundaries, in order to test the relative advantages of broad knowledge and production boundaries. For example, much like an ANOVA analysis, we look at firms with broad market production and broad market knowledge compared to firms with low market production and low market knowledge (Figure 8 details the percentage of firms with broad or narrow boundaries each year during the period of study). To test hypotheses 3 and 6, we used 2x2 matrices (similar to Kapoor and Lee, 2013; Phene, Fladmoe-Lindquist, Marsh, 2006; Rosenkopf and Nerkar,

2001) to compare the effects of different mixes of knowledge and production boundaries on firm survival. Table 5 shows correlations for each category, while Table 6 shows results for the survival models using these firm boundary classifications. Firms were classified annually as broad in tech or market production if they participated in an activity, such as technology production, and narrow if they did not. Firms were classified annually as broad in tech knowledge if the firm had patented in 2 industry relevant patent subclasses (within class 360, 369, and 428), and classified as narrow in tech knowledge if the firm had patented in less than 2 industry relevant patent subclasses. Firms were classified annually as broad in market knowledge if the firm was shipping drives in 2 or more product groups (as determined by Disk Trend Report), and classified as narrow if the firm was shipping drives in less than 2 product groups.

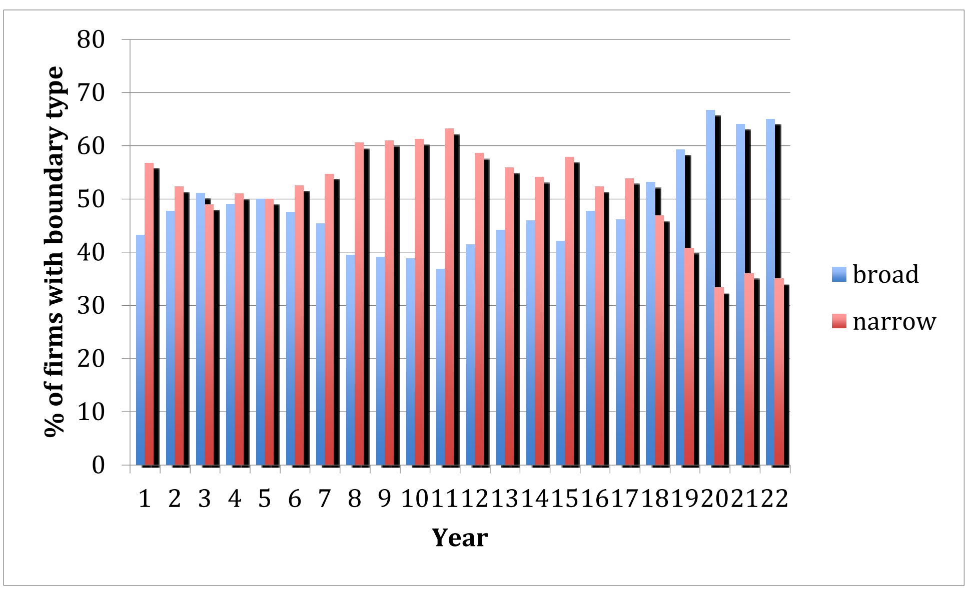


Figure 8. Percentage of Broad and Narrow Boundaries from 1976-1999

Table 5. Simple Correlations for Matrices

		1	2	3	4	5
1	Broad tech knowledge, Broad tech production					
2	Broad tech knowledge, narrow tech production	-0.3705***				
3	Narrow tech knowledge, broad tech production	-0.2879***	-0.1153**			
4	Broad mkt knowledge, broad market production	0.4384***	-0.0913*	-0.0381		
5	Broad mkt knowledge, narrow mkt production	-0.0182	-0.0311	-0.0547	-0.0927*	
6	Narrow mkt knowledge, broad mkt production	-0.2399***	0.1828***	0.1230***	-0.6289***	0.0031

n=766, *** p= < .001, ** p < .01, * p <. 05, + p < .10

Table 6. Survival Models for Matrices

Variables	Model 4: Controls + Matrix Effects for Tech Knowledge and Production	Model 5: Controls + Matrix Effects for Mkt Knowledge and Production
Broad tech knowledge, Broad tech production	0.967664+ (0.509075)	
Broad tech knowledge, Narrow tech production	-0.284869 (0.362620)	
Narrow tech knowledge, Broad tech production	-0.851106 (0.347107)	
Broad market knowledge, Broad market production		-1.19820* (0.565958)
Broad market knowledge, Narrow market production		-1.281718* (0.536118)
Narrow market knowledge, Broad market production		0.313239 (0.211018)
Market size by competitive group	-0.000094 (0.000061)	0.000125* (0.000062)
Average Number of Competitors	-0.020857+ (0.012057)	0.0211955+ (0.011460)
Industry size	-0.001081 (0.000085)	-0.000074 (0.000062)
Era dummy	-0.659182 (0.686322)	-0.186837 (0.388656)
Constant	2.923720*** (0.549179)	3.025350*** (0.642886)
X^2	10.96	19.27*
Log likelihood	-83.89827	-43.35217
AIC	185.7965	104.7043

n=766, standard errors shown in parentheses *** p < .001, ** p < .01, * p < .05, + p < .10

For Matrix 1 in Model 4 (see Table 6 and Figure 9), we tested the effects of the following categories of firm boundaries: broad technological knowledge with narrow technology production, broad technological knowledge with broad technology production, and narrow technological knowledge with broad technology production. We used narrow technological knowledge with narrow technological production as our reference group. We found that when these variables were run with controls, the combination of broad technological knowledge and broad technological production effects had a significant coefficient of .968 ($p<.10$), which provides marginal support for Hypothesis 3: Firms with both broad technology knowledge and broad technology production exit slower than firms with narrow technology knowledge and narrow technology production.

	narrow technology production	**broad technology production**
broad technological knowledge	(0,1)	(1,1)
narrow technological knowledge	(0,0)	(1,0)

Figure 9. Matrix 1

For Matrix 2 (see Table 6 and Figure 10) in Model 5, we tested the effects of the following combinations: broad market knowledge with narrow market production, broad market knowledge with broad market production, and narrow market knowledge with broad market production. We used the narrow market knowledge with narrow market production effect as our reference group. We found that when these variables were run with controls, the combination of broad market knowledge and broad market production effects had a significant coefficient of -1.19 (p<.05). The combination of broad market knowledge and narrow market production effects also had a significant coefficient of -1.28 (p<.05). This supports Hypothesis 6, as the effect of broad market knowledge on firm survival is dampened when the firm also has broad market production. It is clear from our Hypothesis 6 finding that market production assets decrease the positive effects of market knowledge on firm survival.

	narrow market production	**broad market production**
broad market knowledge	(0,1)	(1,1)
narrow market knowledge	(0,0)	(1,0)

Figure 10. Matrix 2

In order to account for potential endogeneity in the technology production variable, I used the Inverse Mills Ratio with a dichotomous variable describing whether a firm manufactured captive drives or not. Captive drives are drives that are both manufactured and used by the firm in its own computer products. Theoretically, we would expect these firms to be more likely to be vertically integrated into technology production than other firms, as they manufacture multiple computer components. I found that this variable was significantly predicted the technology production variable (p=.018) but did not predict firm survival, our dependent variable. Model 2 was tested including and excluding the Inverse Mills Ratio, and results were not significantly affected. Table 7 shows the main effects for Model 2 with and without the Mills Ratio.

In order to account for potential endogeneity in the market production variable, I used the Inverse Mills Ratio with a variable measuring how many firms entered the HDD market each year. Theoretically, we would expect that as more firms entered the industry and competition became denser, firms would invest in marketing and distribution assets in order to differentiate their products and make sure they were addressing large customers' needs. I found that this variable was indeed strongly correlated with the market production variable (p=.000) but did not predict firm survival, our dependent variable. Model 3 was tested including and excluding the Inverse Mills Ratio, and results were not significantly affected. Table 7 shows the main effects for Model 3 with and without the Mills Ratio.

Table 7. Survival Models with Inverse Mills Ratio

Variables	Model 2: Controls+ Tech Knowledge and Production	Model 3: Controls + Mkt Knowledge (prod diversity) and Production
Broad technological knowledge	0.023697 (0.014932)	
Broad technological production	0.700934^{+} (0.384763)	
Broad market knowledge		-0.033153^{+} (0.018263)
Broad market production		-0.293089 (0.307989)
Average Number of Competitors	-0.0278843^{+} (0.014873)	-0.001315 (0.010500)
Industry size	-0.000122 (0.000092)	-0.000079 (0.000093)
Era dummy	-1.017841 (0.851757)	-0.579638 (0.648131)
Market size by competitive group	-0.000013 (0.000070)	0.000071 (0.000086)
Constant	2.954313*** (0.578973)	2.795746*** (0.729270)
X^2	8.43	9.90
Log likelihood	-86.40719	-60.43027
AIC	188.8144	136.8605

n=766, standard errors shown in parentheses *** p < .001, ** p < .01, * p < .05, + p < .10

5.0 DISCUSSION

Our study makes several contributions to the literature. First, we find that when firms encounter systemic change, their market boundaries confer adaptive advantages differently than technological boundaries (technological production produces an advantage, market production does not), which contributes to the TCE literature. In the case of manufacturing, prior TCE literature has stated that firms should base their “make or buy” decisions on cost, picking the least expensive option. We found that in a systemic change context, a firm that manufactures components internally has a distinct advantage over firms that outsource, even though prior evidence (e.g. McKendrick, 2000) has indicated that outsourcing was less expensive in this industry. This finding may be directly related to the status of standards in the industry. When standards are open and technology is stable, firms are able to cheaply outsource components and easily integrate them into their final products. But when standards are closed and the technology is unstable, firms will have trouble integrating outsourced components into their products because their interface specifications have changed. Firms that have both technological knowledge from R&D and manufacturing capabilities are better able to incorporate the new technology quickly, increasing their chances of survival (supporting Hypothesis 3). In our industry context, firms that manufacture technology have a big advantage when systemic change is frequent and standards are in flux. Supplier firms are only able to stay in business when the technology is stable, so when change occurs, firms are no longer able to rely on outsourcing for their component needs, and must manufacture their own, giving firms that already have manufacturing capabilities a definitive advantage over firms that must build those capabilities from scratch.

In the case of activities downstream from manufacturing, past literature has cited the importance of marketing, distribution, and sales to the successful commercialization of a new technology, but we find that they do not necessarily assist adaptation to systemic change. After a systemic change, we found that firms that had these marketing and distribution assets were not more likely to survive, directly opposite to the effects of technological production/manufacturing we found in Hypothesis 2.

Our study also builds on Kapoor and Adner (2012)'s conclusions on technological boundaries by testing the effects of boundary choice on a firm's adaptation to systemic change (rather than architectural or component change). We found several notable differences in results that we attribute to the effects of disruptive change. For example, Kapoor and Adner (2012) found that knowledge about outsourced components (broad technological knowledge boundaries) seems to help time-to-market for completely outsourced firms, but not partially outsourced/partially-integrated firms. This result suggests that to improve time-to-market, firms that produce technology with multiple components should outsource all components (have narrow production boundaries) while keeping the knowledge associated with the components internal (have broad technological knowledge boundaries), or a firm should have both broad technological knowledge boundaries and broad technological production boundaries. In contrast, our findings show that in a multiple component device (although we do not have data on the outsourcing of each individual component), firms that have broad technological knowledge boundaries without broad technological production boundaries do not have an adaptive advantage. We also found that broad production boundaries alone (without the accompanying broad technological knowledge boundary) enhance a firm's survival through systemic change. This finding, in addition to Kapoor and Adner's findings, gives us more insight into adaptation through change. Kapoor and Adner's study focused on a sustaining innovation, where standards were open and performance requirements stayed static, so after a technological change, component suppliers were still able to continue to provide components, and firms with technological knowledge on the components would be able to integrate them successfully into their products. In our context, we look at disruptive innovations with product offerings that included new features but didn't initially meet performance requirements established by previous technology, and standards for interface were periodically closed. Thus, supplier firms were not able to stay in business when change occurred and the standards were unknown, and firms with manufacturing capabilities were better able to survive than firms that did not and had to build these capabilities from the ground up.

In addition, we believe our study's DV of survival through systemic change gives a better measure of adaptation than does looking only at product introductions. Survival through systemic change is only possible if the firm not only introduced a product, but also included the features its customers wanted, and the firm was able to market/commercialize the technology to the new customer base. In the HDD industry, there are examples of situations where a firm shipped a new, technologically sophisticated product quickly but it was not successfully commercialized, which is what a firm ultimately needs for industry survival (e.g. the Kittyhawk drive introduced by Hewlett-Packard). In order to survive through systemic change, firms must match new product introduction to customer needs.

In sum, our study indicates that it is important to study knowledge and production boundaries together, and to consider market as well as technology boundaries. Our findings begin to clarify conflicting results in prior work on technological change and the role of firm boundaries in affecting survival. By drawing attention to the unique challenges posed by systemic change, which upends established product architectures and thus demands new ways of working across organizational and technology boundaries, we identify a contingency that affects which boundaries support adaptation when they are broad.

6.0 LIMITATIONS AND FUTURE RESEARCH

We used patents to measure technology knowledge boundaries, but because of the importance of process knowledge in this industry, we added qualitative data on firms that did R&D but did not patent. However, we cannot rule out the possibility that firms kept their R&D secret and the R&D was not accounted for in public sources like Disk Trend Report, which may have led to our null finding. Future research might look at an industry where IP was less process-oriented and more likely to be patented, to see if this changes the relationship between technology knowledge and firm survival.

We also did not isolate the effects of one particular technological change, but instead observed firms' survival through a series of technological change over a 23-year period. We cannot rule out the possibility that a firms' configuration of boundaries may have been appropriate for one change, but not another, causing the firm to fail. Future research could take a piecewise approach to see what boundary conditions are appropriate for individual changes to market or technological systems.

We did not consider additional moderating factors that could contribute to firm failure, such as macroeconomic factors, or individual firm capital structures. Difficult economic conditions could cause firms to fail more quickly, regardless of a firm's chosen boundary configuration. Firm capital structures may also affect a firm's appetite for risk, which could in turn affect a firm's boundary choices or their choice to stay in the industry. Firms financed by bank loans, for example, may be so hampered by debt service payments that they do not have the ability to invest in expensive manufacturing assets, and thus may be less likely to have broad technological production boundaries to survive through change. These firms may be more likely to diversify out of the industry when change occurs, in order to stay current on bank loans. Future research could investigate the effects of these potential moderators on firm boundary choices and, ultimately, firm survival through systemic change.

Our findings address whether and how firms' knowledge and production boundary choices maximize survival prospects in industries composed of highly fragmented and atomistic competitors, where collaboration is not the norm. In contexts where collaboration is the norm, we would expect firms to use alliances to gain access to technological knowledge, manufacturing functions, and complementary assets necessary to survive through systemic change, thus changing a firm's ideal boundary configuration.

We used firm survival as the dependent variable in our study, but the speed of product introductions is also important to consider, in order for us to observe how quickly firms are able to respond to systemic change with different boundary configurations and to determine how important the speed of response is to firm survival during systemic change. In the HDD context, this would include the speed to introduce a new form factor, after the first one has been introduced (as listed in Figure 3), and the speed to introduce the products with major component innovations (as listed in Figure 4).

We chose to focus on two of the three firm systems affected by systemic change: the technological (defines what a firm makes and includes R&D and manufacturing design) and market systems (defines how a firm reaches a market and derives profits from it). These systems are more easily studied than the organizational system, which defines how a firm accomplishes

R&D and manufacturing through structure and routines, and is internal, not easily codified, and difficult to measure. Future research could not only address the effects of systemic change on organizational systems, but also could address which of the three systems (technological, market, and organizational) adapt first to the systemic change. Although organizational systems' structure and routines inherently constrain what technological and market adaptations can be made, it is not clear which system firms first focus their attention after a change.

APPENDIX A

A.1 INTERVIEWS WITH INDUSTRY EXPERTS

We used this very general interview protocol for semi-structured interviews with industry experts.

Interview Guide:

- **Goals**: To understand the technology and the chronology of technological changes. To discern how often and in what ways technological change in the industry involved systemic changes. To understand what firms had to do in order to adapt to or introduce particular technological innovations – what changes to the product's design, manufacturing, interface with customers and suppliers were required? To understand the different kinds of choices firms made about their knowledge and production boundaries and what the observed consequences of those choices were.

1. Component and architectural changes featured in prior studies of the industry:

- Thin film inductive heads: (1981)
- MR heads: (1991)
- Thin film media: (1983)
- Form factor changes: (1979, 1980, 1983, 1989)

- Were these most important? Are we missing any?
- How did these changes affect the market/customer bases you concentrated on?
- How did these changes affect how the other components worked together?
- How difficult were these changes to incorporate into products?

2. Looking for the following kinds of insights regarding the hypotheses – the role and relevance of particular kinds of technological, market, and functional (value chain) knowledge and activities for innovation, e.g.:

--Do firms that manufacture get insight into component interactions they wouldn't get if they outsourced?

--Do firms that do broad R&D on multiple components have a better shot at betting on the right technology?

--Did firms that did broad R&D but outsourced the manufacturing have a better shot at being able to incorporate tech changes?

--How did doing your own manufacturing affect speed of product introductions?

--How did broad R&D affect speed of product introductions?

--Do firms that do their own marketing/distribution have a better chance at seeing the promise of new markets? Worse chance?

--Do firms that have broader exposure to markets, through alliances and geographies, have a better chance at seeing the promise of new markets? Worse chance?

--Broad patenting a good measure of R&D?

3. Conclusion: Ask for additional contacts

- Is there anyone else we should talk to at your firm (or other firms in the industry) regarding research on the technologies we talked about today?

- Is there anyone else we should talk to at your firm (or other firms in the industry) regarding manufacturing of the components we talked about today and the decision to in-source or outsource?

A.2 NOTES ON INTERVIEW WITH INDUSTRY SOURCE 1- 1-18-13:

Industry source 1 worked at a large HDD firm (433,362 employees) before leaving to work at a disk drive component supplier firm, where he managed applied research, product and process development, customer support and manufacturing. All notes below are his specific comments on industry trends.

- There is no simple pattern to failures

- 1 (IBM) to 50 to 3 (WD, Seagate and Toshiba- Toshiba has miniscule market share and probably won't survive)

- IBM was first- inventor of the hard drive- had 100% market share, but out of the business today- led in technology- major developments were all led by IBM (heads, data channels and coding methods)- here's a case where you have the leader who couldn't make it

- There were companies that for short periods of time were able to be/call themselves first followers behind companies like IBM- but very dangerous world to live in, one slip-up and they'd fall out of the race- kept up with tech through buying the technology through buying competitors and component suppliers who had a better tech capability than their internal capability.

- Just having prowess in manufacturing was necessary but not sufficient to do well. Others failed because they were too late to take advantage of offshore manufacturing- HDD industry was second after semiconductor industry to move manufacturing operations offshore to Southeast Asia to countries like Singapore and Malaysia and Thailand, and now China, but not everyone did it in a timely manner. Those who didn't do it in a timely manner, who continued to manufacture in US or Europe, failed because they had an unaffordable cost structure. Had nothing to do with the component capability or technology, it had to do with simple economics- the costs weren't there.

- He doesn't think there was a pattern to failure/led to these results- there were many many reasons that led to these results- in the end, each firm was a unique case study- had their own unique circumstances that affected their business

- some failed because they made fundamental mistakes- failures included: betting on the wrong technology, company changes in corporate responsibility- restructuring mistakes- moved things back and forth from different countries (losing a few generations of products- which is like losing a lifetime in this business)

- Manufacturing process necessary but not sufficient to survive

- Some firms failed because they were too slow to move production offshore- unaffordable cost structure in manufacturing in US and Europe

- The main customers in the HDD industry were computer makers- Dell, Apple, H-P, etc.- the overwhelming majority of products historically went into desktop PCs- today over 50% of HDD goes into laptops

- those companies insist on having at least 2 drive suppliers for each computer product- doesn't matter what kind of tech leadership a firm has in making a drive, it may just be the first to market it

- won't get serious volumes until a 2nd firm was ready to ship as well because none of the computer companies wanted to take the risk of having only one supplier- every firm has had hiccups in their history of shipping drives- so had to be first 2 or 3 there (3 if product had very high volume)

- industry created de facto standards- if you're first to market with a certain drive, have to wait until another firm was also shipping this, someone might buy a negligible quantity for advertising, but substantive volumes always required multiple suppliers to be there at the same time. The trick for the drive makers was to match the standards (i.e. data rate) and try to positively differentiate themselves with higher reliability (customers happy because higher quality would reflect itself in the quality of the computer product itself) and lower cost (allowing them to be profitable)

- wanted higher reliability and high enough volume and capacity/performance that matched the computer product

- very expensive for Apple to replace hard drives because they fail- they look at total cost of ownership- once you match capacity and performance, then they look very carefully at quality and price. Hard to win in this type of world.

- if you didn't have the latest tech, you would need even more components (extra head or extra half disc to achieve a particular capacity) which increased cost to match the capacity (but offshore helped here and could make it cheaper to do with inferior products- may end up cheaper than something with fewer component manufactured in US and Japan)- so many variables that influenced your ability to survive.

- No one failed because they couldn't get the tech right- but some component suppliers did
  Examples:

- Ampex: pioneer in film disks- Alar film disk which Ampex tried to commercialize in a massive way by betting on electro plated tech to make disk- plating the disk- bet on this, but failure- disk magnetically was fine could never create disk that had a long enough lifetime (mechanical robustness, durability)-high/unacceptable failure rate, had head crashes

- Applied Magnetics: (US)- large head maker- waited too long to invest in MR head technology- stuck to ferrite heads far longer than anybody else, then late in film heads, then late in MR heads, other competitors got there first- went out of business

- Silmag: (France)- had very nifty film head and MR technology on silicon chip- no laborious process of making sliders- all you had to do was dice like you did for semiconductors, but by the time they got all the tech wrinkles straightened out, first with inductive heads- too late to market with inductive heads- failed because of this- lagged industry needs by 3 years (3 generations of product- a year is a generation of products)- impossible to recover from that.

- HDD manufacturers failed b/c of mistakes: where they manufactured (which affected costs), the technology itself. i.e. mistake that almost imploded IBM's business: laptops needed drives that were shock resistant- laptop moves a lot and runs risk of damaging the drive- aluminum bases too fragile- glass substrates more robust hard drives (to this day 100% of laptop drives are glass substrate), but there were 2 issues with these 1. Cost more to make 2. Inferior disk (signal to noise ratio worse, etc.). IBM then moved to 100% glass disks for all its drives, abandoning aluminum substrates for desktops and servers (not just laptops) but needed extra disks to make up for capacity issues- cost too much- glass not as robust in enterprise systems- cost them at least one generation of products and customers- destroyed profitability- caused IBM to sell the business to Hitachi- could no longer match companies' profit objectives.

- 2 companies that did MR head technology (IBM and HP) did tech for MR head- IBM version was reverse engineered by the rest of the industry (they waited for product to come out, took it apart- spent 2-3 years before they mastered the tech and they could commercialize MR heads.

- H-P chose not to make its own technology- chose to use Headway in California- outsourced to Komag affiliate Headway- made wafers. Established a 3 way partnership- H-P, Seagate, and Headway. Headway (later purchased by TDK- only head maker around today) made wafers, H-P provided technology. Seagate then took the wafers, did HGA, kept some for itself, gave rest to H-P. During this process, Seagate learned to make the MR heads by watching Headway (benefited from 20 yrs of research at H-P).

- Some people stole trade secrets, some people hired people from IBM who knew the tech- if someone has a breakthrough significant enough- the others in the industry will find a way to grab hold of it, but the question is can they grab hold of it in a timely manner? With MR heads- 2 different routes- IBM and H-P partnership.

- No pattern for how these technologies came to be and how they diffused- have to look at on a case by case basis.

- Xerox Parc- created all sorts of innovations they never capitalized on- i.e. the mouse tech first commercialized by Apple- 1970s- trying to make a $10K computer with $1K in storage (extraordinary target for the 1970s)- strong effort in film media-but they never commercialized, founder of Komag worked there- licensed this tech to Komag (a supplier)- Komag founded with most advanced thin film tech- beat IBM and everyone else in the market with very robust film disks- because of the investment Xerox never commercialized- better than anyone else's.

- Then you have Headway making heads- so you have Komag and Headway there, so you can start a business of just assembly and try to differentiate yourself by cost or electronic function of drive

- Conner Peripherals- disk drive company founded by Finis Conner, veteran of Seagate- did self-testing instead of expensive testers (which everyone eventually copied- build in microprocessors that would do it for the drive)- much cheaper- then could use component suppliers. Became one of the most successful companies in its era- without any real tech capability- they set off the Komags and TDKs/component suppliers- they differentiated themselves by how smartly they used electronics to decrease cost of hard drive. That wasn't good enough to be a long term strategy- everyone copied- they were eventually purchased by Seagate.

- Seagate started out as an assembler- but eventually realized to survive or thrive, they purchased suppliers and tech capability they didn't have- head and disk making of their own (most notably, CDC- Minnesota and OK). Then eventually bought Conner.

- WD started the same way- bought Read Rite as head maker, Komag as disk maker, and Hitachi's disk drive business- VI-ed

- Seagate and WD smart enough to make moves in VI- enabled them to survive.

- He thinks that VI is the best but there are some issues- internal suppliers become complacent- won't lead on tech or cost- one way to keep the group honest is to purchase ½ of your components elsewhere (the surviving HDD makers do this today, using TDK as their supplier)- helps Seagate and WD rigorously measure capabilities of internal groups and force them to keep up with external supplier

- Component supplier has visibility to more than one HDD maker- can be a learning conduit for new technology- can teach how to incorporate but it takes time. They did this when companies struggled because it was in their own best interest- if the firm failed (because they didn't have the R&D to use the part supplied), they could no longer sell heads to them. It took longer to do this (learn from supplier) and firms would miss a generation- which cost firms a lot- would bring something to market that customers did not use/want because they were behind on technology.

- Firms didn't fail because of not being able to do the new technology- but they maybe underestimated the new tech and thought they could do the same thing with the old stuff- that's what killed them.

- Those that bet on wrong tech ended up missing a generation- were behind on the capacity for next one too. Had to be at the right capacity

- Most companies could survive one miss (missing a generation of products) – no one has survived 2 misses- but too costly to survive more than one. Most firms that went out of business blew 1 or 2 generations of products.

- Misses aren't recent mistakes, it's a problem that began 2 or 3 years ago when R&D should have begun.

- Broader R&D could increase chances of betting correctly. IBM, HP, Control Data, DEC, Hitachi, NEC, Fujitsu all did this- but all these guys (Hitachi just left) are out of business. All had invested in serious/significant R&D efforts.

- The survivors are the purebred dogs, not necessarily the longest living, but stronger and more capable- survivors are those with assembly as their heritage- then over time they gradually integrated and today they are a mixture of outsourcing and VI. WD and Seagate were not pioneers in R&D until recent history.

- All the firms in the industry are dependent on each other's patents- all cross-license- because everyone lives in "glass houses"- only litigious against outsiders.

- Very tight profit margin- 15% (used to be 80% for IBM back in the day, higher than Intel-Windows has now!)- have to be flawless with production in order to survive (50 cents different can be a huge difference)- must be competitive in capacity, quality and price. WD and Seagate succeeded because they were the most ruthless in their focus on cost and execution.

- He predicts that VI/outsourcing now is the good combo for now- but maybe not in 10 years, impossible to predict because no 10 years in the industry were the same.

- Patenting- He worked in the dept at ___ that decided what to publish, what to keep a secret, and what you had to patent (protective of product)- some firms would purposely patent things they weren't actually working on that were innovative and that were not going to commercialize to fool competitors- often surprised them. Very difficult for someone working outside ___ to know what they were really working on. 10% of the patents filed may be useful, 10% of that 10% becomes really significant (1% of all patents). Difficult process to be judge a priori of how successful patent will be.

- Many companies benefited from Xerox Parc before they got their own internal capability. Seagate spent 5 years working on MR heads, but H-P and IBM spent 20.

- IBM was late on film disk- even though they'd been working on it since mid- 1960s- but were late- it was introduced by another firm in 1983, was not introduced by IBM in 1988.

- Manufacturing- speed depended on the company- no general rule- VI groups could become complacent.

- But did this manufacturing give you knowledge that helped you through a change?

- it helped you in time-to-market, could also help in quality (if you ran cleaner facility, would affect long-term reliability and customer satisfaction)- would pay more.

- ruthless- beat them up on quality, price, and warranty terms (would return products that did not work)- made suppliers more diligent, and paid attention to manufacturing technology and location. Not everyone was as diligent with these details- but this is why these firms survived.

- Manufacturing quality and location mattered: Location off-shore provided the firm with a cost-effective labor force (1/20 salary of same engineer in silicon valley), subsidies- tax holidays- no taxes or duties on products for the first 5 years and ever after if you improve your factory (WD and Seagate were pioneers at this).

- Differences among companies in recognizing new markets:

- i.e. Seagate saw IBM PC as a market, even though IBM did not, Integral Peripherals saw mobile opportunity.

- Usually new entrants/startups found the market for new form factors- then big firms entered when it got big enough. Only after they demonstrated that these moves were significant did established firms move to offer that product as well.

- He does not think diversity of market exposure made a difference: profit margins seemed too low to make it worth it.

- Book- The Innovator's Dilemma- not everything he writes about is accurate, but there is a strong grain of truth

- IBM knew they needed a drive for PC- but they had no idea how to make a drive to meet that cost target- they were making Ferraris and they wanted a Volkswagen and they didn't know how to bridge this- but only 20% gross margin (1/4 the profits of what they were currently making) and as far as they know the success in a particular marketplace will sustain them forever- but have to be a visionary to see that things could slip.

- It took Al Shugart to recognize importance of PC- but he had to leave IBM to chase this.

- Latecomers made it to the market eventually (IBM was a latecomer to mobile market, but still got 50% of the market when they entered)- but even with successive changes, firms had trouble judging what markets to go into. 2 instances where IBM pioneered- RAMAC and the microdrive which had a short life towards the end of the time they were in the industry- everything else they waited for others to pioneer.

- WD and Seagate were both late to mobile market- but both have presences now.

- Outsourcing marketing and distribution could help but not always- needed to sell drives to your competitors in HDD (like establishing relations with North Korea), which was difficult. IBM attacked this problem by hiring marketing people with experience in those channels- took too long to develop- hired people from other HDD firms and customer firms.

- THEME: Lots of successes and failures and difficult to compartmentalize/categorize failures. Usually it's an "outsider" person- he used the words "maniacs with a vision" (from within the company or outside it) who instigates change- hard to make a revolutionary change inside a big firm.

- His response to my thesis hypotheses: 4 core competencies a firm needed to succeed in HDD: 1. Research 2. Manufacturing 3. Marketing/Distribution/Sales 4. Service- need to be strong in all 4 functions- and they all must be highly interactive with each other- have to be connected on a regular basis- hard to do when outsourcing.

- Could look at companies business units- why were some successful and some failed and strong collaboration.

A.3 NOTES ON INTERVIEW WITH INDUSTRY SOURCE 2- 1/23/13

Industry source 2 spent over 30 years in the industry at a large HDD firm (433,362 employees) on the technology side of the firm, where he was one of the inventors of a major disk drive component technology. All notes below are his specific comments on industry trends.

- He was in the garage so he says he was weak on the dates

- 1956- first disk drive- RAMAC- 30" aluminum disk (magnetic recording surface), coated with brown paint (iron oxide) a spinout process. Metal head (little inductor with a gap in it, so you had a coil wrapped around the little gap and that magnetizes the stuff on the disk). The head and the disk were the two major technological pieces. And with the head I include the air bearing that keeps the head from hitting the disk when it goes by. The third thing was the electronics. If you ever saw a RAMAC, it is the size of a double wide refrigerator. It's hooked up to the electronics, which is a set of vacuum tubes, huge also.

- During the evolution, there were lots and lots of changes: 3 big changes: 1. change from a particulate disk (paint) to thin film disk media 2. change from conventional recording head to a MR (magneto resistive) head 3. change from giant control units to a small, relatively compact circuit electronics thing you put on the drive.

- my own specialty: thin film head and originally it was a regular magnetic conductor thin film head, although he started working on both of them in 1969 or so, 1970. So as far as I'm concerned, the thin film head, and the inductive head and the MR head are at pretty much the same time, but from a product point of view, MR head took 20 years (came out in 1991), thin film inductive heads was much earlier, at least 10 years earlier.

- The reason that the MR head was a bigger change than the thin film head was because the thin film head, in some sense, was a drop-in replacement for the previous inductive head, which is a ferrite head, which is pretty much a drop in replacement for the original metal head. If you showed someone who worked on the original heads and you showed them the ferrite head which was a magnetic material and smaller, and then you showed them the thin film head, well, we got rid of the ladies with the needles who were trying to wind wire around an infinitesimal gizmo and replaced it with thin film fabrication techniques. But they're all essentially the same, so there's no trouble- if you understood one, you would have no trouble understanding the other. And the MR head, of course, was a different animal entirely.

- I used to give the newcomers a kind of little lecture on why the MR head turned everything upside down. Previous heads, when you went from one generation to another, was a big deal in head department, and you also had to talk to the guys who had to decide what voltage of currents to run through it, but other than that, they're all pretty much the same, they affected mostly the head department. When we went to the MR head, we had to change of course, the head department, change the disk, because, well I can tell you why, but we had to coat the disk. We had to change the electronics, the equalization as it's called- the signal was different. We had to change the servo dept because up until that time, the same recording head wrote the track and read it (a single head device). But an MR head only reads, so you had to build it with an inductive head stuck on top of it. And since they're never exactly in the same alignment, you had to get the servo people to switch a little bit of track switch every time you switched between reading and writing, partly a big deal because by that time, even when you were writing, between that receptor you had to read the servo information which tells you where the head is positioned. So it changed all of that. Then you also had potential corrosion problems, so the people who were in charge of the atmosphere within the drive had to change what they were doing and then there was endless testing, and it turns out these heads were susceptible to electrostatic charge, static zap. So if the ladies wiggle their butt on the chair and get an electrostatic charge while assembling drive, it would blow up the head. So there was a whole new testing regime, a whole new manufacturing procedure. If I think about it more I'll probably come up with other departments that were affected. But the short answer is, changing from a thin film to an inductive head was small potatoes compared to affecting everybody when you went to an MR head, and that's one of the reasons why the industry lagged behind a while.

- Between the MR to GMR head, there's a significant difference inside the head, but to the outside there seems to be no difference at all, they behave exactly the same, it's just that GMR head has a bigger signal. Well, you can say it was a very important development because it let you make the heads smaller to get the same signal, which of course was what every new generation of drives has to do. So it was good that way, but it was not an upheaval.

- Here's another example: in a disk drive of those days, probably even still today, there are inevitable contacts between the heads and the disks. Because you just can't make a disk smooth enough, because you're flying so close, you could never get a speck of dust in there, but even so, any little ripple on the disk touches the head, and didn't affect the inductive head except it might wear it, but an MR head was thermo transient (drove electronics crazy), so there was a long and difficult set of work in the electronics side and in the channel side, to deal with the thermo-transience. So they just didn't exist before that. Imperfections on the disk when head goes by, it actually mechanically touched, it didn't have to be a magnetic particle it touched, often it was just a speck of something that was there in the disk manufacturing process, but as it went by the head, it caused a little thermo blip indistinguishable from a magnetic blip, so it drove the channel crazy.

- Form factors: every new generation of disk drives shrank the components inside them. If you wanted to cut the loop on the areal density, you had to cut the track length in half and the bit length in half, and in the early days, you didn't want a time, you first cut the track, and put out a generation of drives with twice the capacity. And then you put twice as many bits per inch along the track and that would be the next generation. Then you would go back to having the tracks again. And each time you do that, you have to make the magnetic grains on the disk had to be finer to keep the signal from getting read, you made the gap in head narrower to get more BPI along it. You had to make the width of the head half so you could get twice as many tracks per inch. But those were just evolutionary and they went on for many years. Everyone knew what their job was, you would have a smaller signal so you had to do something to filter out the noise. If you were increasing the linear density you had to fly closer by a factor of 2. So all the air bearing people and wear and reliability people had to worry about that, but they knew what their orders were. But the MR head was a new set of orders. In addition to all of that, there was more.

- There was one major evolutionary change- the thin film disk- to get rid of the paint, and that was very difficult for the disk people and the reliability people who had to worry about lubricating and wear and so forth, but it didn't affect the other departments very much

- Perpendicular recording- it actually is a modest change in the head department but it's a big change in the disk department. And the reason is, in the original longitudinal recording, the magnetic field that writes is produced by the head and nothing else. Whereas in perpendicular recording, part of that head is in the disk. So when you energize that head for the field, now you're producing a field that is perpendicular to the disk. So it goes through the recording layer and into a software which is effectively part of the head and closes the magnetic circuit. So a big change to disk people, to the head people, the write head looks a little different, the read head looks the same. That isn't really affected. The write head, instead of being in the shape of a letter C with a gap, now it's in the shape of a letter I and points down at the disk. Then somewhere there's a return path much larger that closes the loop. But it doesn't write, the writing is done by the point of the little I. So it's a significant change to the head but it's a terrific change for the disk.

- Got into this because when you shrank the size of the recorded disk, there's a signal noise problem, the head signal gets lost, but also, the number of little magnetic grains in the disk shrinks too, so you have to make them smaller. Because if the number of grains in there gets to be less than 20 or 30, then the signal gets really ragged, and you have trouble telling a 1 from a 0. So the problem is when you shrink the size of everything, the little permanent magnet gets magnetized and it has a certain amount of stored energy in it. And you have to put the energy in it to flip it to the other direction. And when you scale the size of the grain by 2, it changes the volume by 8. And the energy in that same material for the grain, half the size, is 8 times lower. It still takes just as big a field to write it. But the problem is that the little magnet is bouncing around with energy of "kt"- Thermal noise is ubiquitous in physics- unless you are at absolute zero, it's never quiet. If something can bounce around, it will bounce around, and the amount of energy, that's on average, is kt. Ordinarily it's a very tiny amount of energy so you don't see things bouncing around. When the grains get small enough, this bouncing around is enough to make them flip and flip back and then the disk is completely erased. So if you keep scaling down the medium, eventually you get something that won't work at room temperature, which it has to do. Only way you can do that is use smaller grains with smaller magnets- takes more energy/longer to flip. The new magnets are much more powerful than the old ones used to be. Very best magnets now 50 times stronger, it takes 50 times as much energy to flip one. Rather than shrinking down the disk, eventually they ran into this problem and they had to start using stronger and stronger permanent magnetic materials to write the data on or else it would self erase. Stronger materials take a bigger field, and pretty soon, you get the permanent magnet grains you can't write with a write head and you might try to make better and better write heads but eventually you run out of juice there. There's a reason for that, because the strongest soft materials that you could make a head out of are iron cobalt and when you saturate them, you reach a point where there are no better materials to make your heads out of. Then it was realized that perpendicular recording would get you at least a factor of 2 in this problem, just because the geometry is better (the materials you can make it out of allow you to use smaller grains). Big deal with disk media group people- change of materials where data is stored but you've also got all this soft stuff and layers that are needed in order to complete the head.

- 3rd big change- evolutionary- Electronics- changed from vacuum tubes to transistors to integrated circuits to million transistor integrated circuits and suddenly something as big as a refrigerator was now on a chip, and you can actually put it in a little disk drive instead of in a separate giant box. Evolutionary change- not a single product change like MR heads. If you wanted to point at something- 8" and 5.25" drives (because before that the disks were huge with giant control units)- huge shrinking in 1 product. Allowed a lot of new applications for disk drives, not just data center at the bank anymore.

- More departments than you know. Tribology (science of corrosion and wear- deal with reliability)- head crash group- when they went from particulate disks (iron oxide- not very magnetic) to thin film disks- big change for them. They had to work really hard to come up with a way of lubricating a metal- once you go to metallic (iron oxides not very magnetic- went to thin film because they needed stronger magnets)- head crashes, nicks the protective coat on the disk and then corrodes (rust) the disk. When you went to an MR head, you not only had to lubricate it and keep it dry, but you also had to put in an insulating layer because when the head hit the disk, it was actually an electrical short and you can't have that (used carbon overcoat had hard carbon, an insulator to protect MR heads from shorting out when they touch the disk).

- Just like dreamliner- one thing affects other things. Lithium manganese cobalt battery- burns without energy (like a bomb).

- Air bearing also in tribology department- wear-in process. Only the very first disk drive, the RAMAC, used an air bearing from a pump, all the others are self supported air bearings, which means they started contact, but as they get going the air being sucked under the head builds up a little pressure and the head floats, but during starts and stops there's lots of it, so you have to worry about the wear in that process.

- In the old 100K drives, the company did everything, they built all the parts themselves- it was too complicated and there was no independent component business (Companies had to be totally VI-ed at first). 3 or 4 companies doing this.

- After awhile, little firms popped up as component suppliers (making heads, disks, electronics, lubricants)- only existed in a stable evolutionary environment. When there was a big tech upheaval (like from particulate to thin film disks, half of them would go broke because they couldn't do the integration testing and the development needed to make sure the heads and disks and electronics all worked together-these firms would not have enough R&D to make the new components) would go bust.

- So you would see the big companies put out a standard technology. And after a few generations of that, people would start copying them, often staff hired away from the big companies, would either make cheaper drives using the same kind of technology or they would just make components and sell them to other people. Then a big changes, and half of those guys were gone- very tough on them. Couldn't change technologies without being in bed with a disk company.

- Continue to make old tech at low price, new tech very expensive development-wise- so even though new tech was better, they could compete for awhile and then sort of taper off. Once that new technology was established, they would reverse-engineer and hire people away to get the technology. Come out with equivalent product 1 or 2 generations later.

- There are certain companies that buy disks and heads from other companies but they get closer and closer together until one of the drive companies just acquires them because they need stable supply and tight integration.

- There's 1 or 2 independent head companies left, and few drive companies at all (Seagate, Western Digital and Toshiba).

- IBM as a matter of policy, you would buy 10% of your components from the outside just to keep your inside guys honest. But you'd have to buy enough to keep the little guy in business.

- If technology reaches a dead end- can't make disk any smaller because you can't find the right materials to do it, then you might see component makers again, but only if there's enough disk drive companies left to make it matter. But only 3 companies making drives anymore, which may not be enough to keep the independents alive.

- Product development- the first thing you do is try to integrate all the components together on the bench (make new parts work with device) and put in test drive and work on the tribology. He always worked in research area but was called in enough times to product development to help them out of a hole- even if you know what you want, but the key is scaling up the production line. If you can make a few 1000 and they work perfectly, then you go to 1000/day and it all falls apart. Key to profit and reliability- get the manufacturing stuff right.

- I can think of more examples of where we outsourced the assembly of the drive. You can outsource components if you can establish tests for the components and test them all the time (both at the supplier end and the receiving end). Can essentially use these suppliers then, but not easy. Component suppliers managed the work with low overhead and quick turnaround (quick and lean), whereas big companies like IBM still had huge overhead.

- Gave the component suppliers the key parameters (current and voltage, distance off disk, give them a few disks they can test with the heads)- write a whole set of specs.

- Parts you made yourself didn't always work, which was a major reason for having a second source.

- Non-disclosure agreements- worried about whether component suppliers were sharing (if they were also supplying your competitors)- don't want them to know what your specs are. IBM used component suppliers the least of all the major firms.

- Did product come out faster if you did your own manufacturing?

- Trying to ensure smooth flow of production- want other suppliers if there's a hiccup in your factory. IBM had 3 factories making heads, if one went down, it was good to have some independent suppliers qualified to make that part.

- Seagate started out using all outside suppliers, but gradually did it themselves because it's much easier to develop a new product using in-house components. You know exactly what you've got.

- Made first MR heads in 1970 and first working inductive heads in 1970s- recognized that MR heads not an obvious choice for HDD- with an inductive head, you get a voltage out that's proportional to the rate at which bits go by (the velocity of the disk). With something like a tape drive, which is 100x lower velocity, the signal is a 100x smaller, the MR head doesn't care, it's independent of speed. Early heads were used for magnetic stripe cards at Macy's to read price tags just like credit cards, sensing magnetic bubbles, tape drives much earlier. IBM made these- so very broad R&D and product placement.

- Problem solving: That's when you would use your broad R&D to decide what to use to give you transfer rate, capacity and reliability demanded.

- With every tech change there were people who argued for keeping the old technology. Every time a new product cycle started, they'd name a product manager to talk to R&D for problem solving- manager would have to decide what to use after talking to R&D. So example of a problem: too small of a signal, having trouble writing, need more capacity or reliability- MR heads were the answer.

- MR heads were on the table for a long time before they were picked up. The product manager did not want to be the first guy to use a new technology, because it cost an enormous amount to do that, came out of his budget, cost to his profit, and lost reliability, took a long time to get this back.

- R&D- Consultants to product developers, invented things on the side (MR heads and thin film inductive heads fell into this category).
- Many people patent things that are dreamed up but that they cannot make!

- By the time MR heads came out- patents were expiring for that tech. When you patent something, telling the world what you're doing. If you know something will take a long time, so you're torn- do you patent? What about coworkers who leave (could patent it at next company)? Can't publish without patenting. Can patent things you can't make.

- Thin film inductive- a process more than knowledge and process patents were not enforceable (although did get a good patent out of that- patent the wrinkles that come out of the process- the shape of the little magnetic pole tips and the shape of the back of the thing- patent what you got out of the process- what was needed to make something work)

- Printers, typewriters, machine guns (WWII), mechanical company with a mechanical background that grew into computers- invented the business computer, had to invent the disk drive, made some of the first tape drives- try to innovate based on what could be better/less expensive. Being exposed to all these industries enabled them to come up with different ways to solve problems.

- Answer to thesis question: If breakthrough can be contained in 1 area, not as big a deal as multiple departments, need to be VI-ed if new component is not a drop in and multiple disciplines are involved. Need to know all the things they tried and didn't work, so reverse engineering has its pitfalls too.

A.4 NOTES FROM INTERVIEW WITH INDUSTRY SOURCE 3- 1-25-13

Industry Source 3 was formerly CTO at a large HDD firm (57,900 employees), and spent 27 years at another large HDD firm (433,362 employees). All notes below are his specific comments on industry trends.

- IBM: the issue wasn't a technology problem, it was a culture- speed-business process problem

- Clearly they had the technology development, IBM made huge investments in research for magnetic recording and everything from components to electronics and interfaces, but the problem they had was that they really didn't have a process for moving that advanced technology into products.

- Some of it was culture. There were cultural barriers between R&D and product development. ___ can tell me something about that as well- since he worked at IBM research for a number of years, he can tell me about it from that side, but ___ has a view of it from the product development side.

- IBM of course founded the industry, founded on it based on a business model that was focused on the enterprise business because only businesses could afford the price of the early disk drives. They built a huge huge business in enterprise and computers and disk drive systems and subsystems and they really struggled (and I'm sure you've read the Innovator's Dilemma) when the PC business started- they fumbled that ball rather badly from both a software point of view and as well as from a hardware point of view. The enterprise business they had been so pre-eminent in for all those years was based on a business model that required huge margins- huge gross margins.

- Their semiconductor business for example, was running at 70%+ gross margins, their disk drive business was as well, and when small companies began and the PC market began to develop and their became a driving demand for low cost rotating storage, other companies didn't have all this overhead and all this infrastructure and they could survive on a 20% gross margin instead of a 70% gross margin.

- IBM kind of figured it out, though they had another problem- it was a centrally managed company- all the major decisions concerning investments and strategy came out of Armonk, and so the operating divisions couldn't manage their businesses independently- everything had to go through Armonk for final approval make decisions. They had a business process and structure issue that just slowed them down so much, that they didn't respond quickly enough even though they really could see it coming. It was fascinating to watch and probably still have today one of the most sophisticated predictive capabilities in their organization in terms of where technologies are going, where the business is going, where the markets are going. They understand all of that, but just couldn't make the transition fast enough.

- So speed was a problem and that's sort of the high level overview of the business and infrastructure issue that IBM was dealing with in the early 90s/late 80s.

- They recognized that issue that they had.

- Because IBM was pre-eminent in enterprise business and in the 50s, 60s and even 70s, there were no competitors- and so IBM's answer to that was to set up different locations, different divisions, located in different parts of the country, and give a couple of those divisions the same responsibilities and had them effectively compete against each other for resources. (i.e. they set up a development organization in Rochester, Minnesota, for example, that had responsibility for low end disk drives, and left the responsibility for high end disk drives in San Jose). The idea was that the Rochester team would not have the cultural barriers or cultural issues and business issues- but the problem eventually was that they ran each independently for a short time, and eventually each of these independently run divisions was folded together into San Jose- they felt threatened and had control of the funds, so they squeezed off. Maybe not on purpose.

- As the world changed, as the PC business got started, computers and the storage systems that went with them went from these highly unique systems in fairly low production to a commodities type business, where manufacturing was king in many ways.

- What about the technology things going on in the industry?

- MR heads, thin film heads and media- difficult technology transitions for the industry to make, but at the time, in the early days, IBM was very pre-eminent in those technologies, in terms of their research understanding. The problem they had was that they couldn't translate that to product development. So there was this kind of cultural barrier between IBM research and product development that slowed the transition of technology from research into product development. One of the huge issues for the enterprise business was that reliability was king- using the new technology was a very dangerous thing. If you moved to a new technology too quickly into a product in the enterprise business and it was embryonic and had some kind of teething pains then you ended up populating enterprise systems with a problem that was going to be very very costly to fix. So there was a natural reluctance to new technology going rapidly from research to products.

- Knew tech changes were coming but couldn't move fast enough for 2 reasons: 1. reluctance on part of product development team to move these new technologies into the products, because they had a huge install base that required enormously mature technology, they wouldn't risk putting an embryonic technology into the products because the business impact would be so great. At that particular time they were coming off of a very serious problem with particulate media- and even conventional heads- where there was some kind of vapor in the manufacturing process that was changing the properties of the lubricant on the media, and they would get stuck heads in the field, so the customer would shut the drive down, and restart, or when they went to restart, it would rip the heads off the suspension- so this was at about the same time that the industry was transitioning to thin film media and thin film heads. So the product development team was exceedingly worried about moving new technology very rapidly for fear of creating another hugely expensive- and this was hundreds of millions of dollars to fix that problem with the sticking heads. The industry struggled with this as well. (2) Cultural divide between IBM research and product development. IBM research folks had been run very very independently, they had independent funding, they worked on whatever they wanted to work on, and IBM figured out that they really needed to take advantage of that great resource in IBM research, and so they began to assign IBM research members to product development teams to build a pipeline of translation from IBM research development into product development. That helped, but it was too little too late. And it took a while for the research team- many of them didn't really want to work on product development. And there was a little bit of arrogance on the side of the IBM research team as well. Product development folks made to feel like second-class citizens.

- IBM had the technology but just couldn't move it quickly into the product side, and the big difference was, they had a different market than the PC market. The PC market folks- the Seagates of the world, the Maxtors, the Apples- all of those folks were, as the Innovators Dilemma points out, they were all focused on a new market that would tolerate some missteps and miss-starts and some technology issues in exchange for low cost

- Part of the cost structure of IBM was proving a new technology was indeed very reliable- so they would build hundreds of hundreds of expensive devices to make sure they weren't introducing and immature technology into the enterprise business. So that's the kind of barrier that prevented the leader in the technology development from a research point of view from transitioning technologies quickly into products.

- Thin film head transition came at a time before or simultaneously with the embryonic development of the PC business. So thin film heads and thin film head media were just transitioning at that time, so that's a time when IBM was living that problem (would have had to test the new tech in enterprise systems first).

- MR heads actually got introduced first in IBM in the low end of the business (he was the product development manager at the time for that). It was introduced in a product called Corsair which is a 3.5" 8 disk stack disk drive- standard form factors. So IBM's introduction of MR heads into disk drives to the world actually happened in lower end business. Not necessarily PCs but intermediate systems and then PCs came a bit later. By the time PCs were there, IBM was building disk drives in Japan, trying to get the low cost structure to solve this margin problem that I described before, and they were building 5.25" and 3.5" disk drives with older, Winchester technology in Japan for the internal

PCs. The other issues IBM had was that anything that was made internal was kept internal, had trouble being willing to sell their technology

- Totally vertically integrated, couldn't get economies of scale in manufacturing without selling low end disk drives to other folks, other companies. So the economies of scale did not come as quickly to IBM as it did for other folks.

- They started out- not selling into the OEM business. The 5.25" disk drives were developed for internal IBM system platforms, as well as the 3.5" disk drives, and those divisions were not allowed to OEM those devices. So IBM was protecting their technology by not selling it to other companies. They were trying to protect their PC business, for example, by only allowing Fujisawa, Japan to ship disk drives for IBM PCs, wouldn't let them sell them to HP or Atari or anyone else in the early days. They finally changed that but it was again too late. This gets back to everything getting driven out of Armonk, so these were strategic decisions that were made at the company but the decisions came too late. The decision to participate in the OEM market as a supplier of components came too late. It allowed the myriad of other disk drive developers and manufacturers to get a strong foothold because IBM could not get their cost structure under control fast enough.

- Other firms supplied IBM when IBM could not address their own demand. The PC market grew faster than anyone anticipated-

- PC business- set up as an independent company, and removed the barriers of requiring them to buy only internal components- first division within IBM to remove VI requirement. Their source was wherever they could get the lowest price components, whether it was disk drives or silicon, whatever. Of course the Fujisawa folks then had to compete on an OEM basis- smart thing to do but they did it a little too late. So it put Fujisawa Japan on the same footing as the OEM suppliers and forced the portion of IBM how to figure out how to behave in a much more cost effective way, both from a product development perspective as well as a manufacturing point of view.

- I really think that the long term strategists could see the emergence of the PC market pretty early. In fact IBM did a machine called the 5100 which was a basic ATL machine that weighed 50 lbs and would fit underneath the seat of an airplane, but that was really the first commercial portable computer. Albeit not very portable in today's standards. But that came before PCs. SO IBM could see this coming and set up PC business as an independent company because they could see it coming. They saw it coming but they just couldn't react fast enough. Of course the margins in the PC business got- they went from 20% to 5% as many many new companies got involved in it.

- Margins were not there for new markets to make it worth entering. They exited disk drive business eventually for that reason- because the margins were not there. And they said- this was all part of a major transformation of IBM from a major vertically integrated company focused on hardware to a sales and services kind of company, with software. IBM made this huge huge transition, in the 90s, driven by the fact that they just couldn't manage the low margins, couldn't survive in that world, so they changed the direction of the company in a profound way, and I'm convinced that they would have failed if they hadn't done that. It's unusual for a company as old as it was at the time, 70-80 years old at the time, to make this huge transition, and its business model, driving 400,000 people in a new direction. So again a result of IBM being able to look at the future pretty well, they just realized that they were never going to get their cost structure to the point where they could survive the low margins in the PC business, so they decided to exit it and go in a new direction.

- He thinks they moved into the PC business thinking that margins were going to be x%, and they ended up being x-20% or something like that

- High volume commodity business- IBM didn't understand. They didn't think they thought the PC business was going to become so commoditized with the resulting margin erosion that happened. Once they figured that out, they just got out, closed the business down.

- Emerging technology- there are early adopters and the volumes are low. Which is why big companies like IBM will move late into a market. It's a matter of scale, so in the early days- IBM didn't think it was worth going after 3.5", 5.25" disk drives. I remember the discussions- "oh, there's not going to be enough volume there. There's an arrogance in the enterprise, high end disk drive business that the 5.25" drives were second rate and didn't have the reliability that was needed, they were never going to make it.

- For small startups, what seemed small to IBM (50K units/yr or even 10K/yr) was a big deal to a startup. Seagate was Al Shugart in a garage. Able to grow their infrastructure and scale it as the business grew (didn't have millions of dollars in salaries to pay every year), whereas IBM and other big firms like Imprimis started with a huge amount of overhead and just didn't think this low end was going to grow as quickly as it did.

- Those startups decided to become component (disk drive is component in a system) suppliers (i.e. Conner Peripherals, early Seagate)- bought parts wherever they could buy them, were buying from old CDC- Winchester heads from CDC in those very early days. PCs at the time using tape drives- so even 1 MB of rotating storage in HDD was a huge improvement over tape. I can remember the early PCs that ran on tape drives, the big deal was the next generation that came out with a disk drive, and it was very expensive compared to tape. And as soon as the scale began to develop, there were the early adopters who would purchase the early rotating drive PCs, as those grew in volume and costs began to decline and economies of scale came into play, the 5.25" disk drive just dropped dramatically until it displaced the tape drives.

- i.e. Conner Peripherals supplying disk drives as a supplier to H-P for PCs- the big system houses like H-P would be trying to enter a new market, like a notebook, so they would go back to the drive supplier, in this case, Conner Peripherals, asking for a smaller drive, they were going to scale down the size of a computer to the point where it can become even more portable so I need a smaller disk drive. (NOTE: they found out about the new markets from their customers (H-P) who wanted to make a laptop or notebook or whatever). The other thing that happened of course was the areal density was doubling every 12-18 months, so the capacity of a disk drive soon outpaced the needs of a very low end entry level computer, and so the size and power requirements of the silicon was dropping at the same Moore's Law rate, so it became obvious to many people that if you project that into the future who thought notebooks would be possible, even if a whole bunch of people did not think the market would be anything. Same argument people used when the markets for PC started- low level, entry-level device has a- only meets a modest set of requirements but it's enough to get it started.

- The system houses that were looking to do notebooks or whatever emerging markets would go to their supplier and ask for smaller drives. Then Maxtor's (or whoever's) marketing people would go back to product developers and see if it was possible and start a new business line.

- The folks at Seagate slow at this- Conner much better (did early 2.5" drives)- bought Conner (and it's 2.5" disk drive business) to solve this problem of late market entry.

- These startup companies had very little advanced technology work- were pretty market-driven. They'd wait for someone to ask them for something smaller. Margins were so low- they couldn't afford the R&D unless they know the market is there. Seagate was a very large company when 2.5" business started, Conner was a startup (first product was 2.5" drive)- Innovator's Dilemma type thing where new startup came in at very low end and established company was late to come to market. The reason it happens, in the generic sense is that lots of startups (9 out of 10) fail- because they picked the wrong market, usually.

- So Conner Peripherals was the 1/10 that survived this vetting process that the market superimposes on startups.

- Head media, silicon- what the startups really did was (Seagate, Conner Peripherals, etc.) became technologies integrators instead of innovators, used component suppliers who copied innovations.

- The first Seagate drives were Winchester technology- were able to buy ferrite heads at low cost because the production lines were already amortized, already paid for, so companies were willing to sell ferrite heads at low cost because they weren't making any capital investments in the manufacturing process (industry was transitioning to thin film) so they were just sort of milking old manufacturing technology and ferrite technology. Seagate purchased their heads from Imprimis (CDC at the time) who copied IBM's Winchester technology for their disk drives. So those ferrite heads were available in the marketplace. A couple of firms making particulate media- in this case for CDC's drives- so the evolution of the media industry was a little bit different. CDC made its own media for awhile but also began to buy outside. The particulate media was available to Seagate as well, and they would buy silicon from all the silicon suppliers. Unlike the VI-ed IBM, who developed the technology and manufacturing processes for all those technologies.

- Used old tech first in the emerging markets- as markets matured- would use newer technology as suppliers were able to copy it.

- When IBM introduced first MR heads into 3.5” disk drive business, they were never able to capitalize on it because they had a too high-cost infrastructure. So as MR heads became available from companies like Read Rite- later than IBM- significant amount of time- 3 years or more, might even be 5- because it was a very difficult technology. But IBM at the time would not sell its MR heads to anyone- Seagate even approached IBM to purchase MR heads and IBM said no.

- Flaw in IBM’s thinking- unwillingness to participate in OEM business at any level- disk drive or component level- was a major error. IBM would not supply any components to the other HDD firms- wanted to protect their IP- but someone could reverse engineer the technology. So protecting your IP that way is fleeting- doesn’t last very long.

- It got to be a thing of scale- why was Read Rite successful? At some point in time their production surpassed that of IBM by a significant amount. So economies of scale in manufacturing began to play heavily into the equation.

- Seagate (so small they had no choice) started as an integrator- very little technology they put in themselves- bought head, disk, silicon, motor, actuator, put a little electronics on it, minimalistic control on drive- control was from computer itself- STL-05 control in early days. Very first 5.25” drives in the market from Seagate had this very low level interface. Did a little bit of engineering to hold things together, a little engineering on actuators, put very simplistic electronics on it that would interface to the computer and the computer controlled the drive. Very simple interface. Mature technology for ferrite heads, and for oxide media, for read write electronics, head suspensions, motor technology (although this was one of the things Seagate moved in early on because in those days the motors were pre-embryonic and not very developed yet for those small drives).

- Think of the startup disk drive companies for the 5.25” and the 2.5” as component integrators, that’s really the service they provided. They did no component development, if they needed a read-write head, they went to the silicon house and had them design it. They would wait for the next generation head or the next generation media technology. The media companies were working on, how do I get a better oxide media? How do I polish the surface to reduce the fly height, so the sort of thing that happened next was that the Seagates became systems integrators but began to develop really tightly coupled relationships with the component suppliers. Seagate would share test results of number of start-stop failures, because they would do the system testing of these components. Long term flyability testing would get done by the Seagates and the Conners. Not with the rigor that IBM did with its enterprise business but enough to get the reliability good enough to manage the entry level emerging markets. That’s the way that business evolved. Western Digital came along at some later time, there was a whole set of media and head manufacturing companies that grew and evolved around these disk drive integration companies like Seagate and Conner, and Western Digital.

- Component suppliers did not work together, company like Seagate would source current production from several, maybe 3, head suppliers. So as the component suppliers made the transition from ferrite heads to thin film heads, and then the big difficult jump to MR heads took 5 years (which is actually not that bad- couldn't have done it any faster)- Seagate would provide a test bed- did the system integration coordination.

- The MR heads required totally different set of electronics to drive it, the amplifiers and write drivers were seriously different and had to account for some pretty challenging issues with MR heads in early days- so Seagates of the world would be the coordinator of that technology. So they would figure out some of the anomalies in the MR head for example and go back to the supplier with the right electronics and say "I need this to be current sourced in this way, I need the read amplifier to be able to overlook a certain kind of noise, so there was that kind of system integration, a very technical system integration function that was provided by companies like Seagate, Maxtor and Western Digital.

- Would have to expend more R&D dollars (which was actually spread over many firms, since all Seagate and firms like it would do research on systems integration outsourced parts, the component suppliers would do their own research on each individual part) at that time- those who chose not to do this were not able to stay in the business. They couldn't beat time to market by waiting for someone else to do systems integration, they'd be waiting too long.

- There were also back channels where information leaked from the first movers (IBM)- people would move from 1 firm to another and take the info with them, IBM would sometimes litigate, but it was already out.

- The 20 years IBM took to develop MR heads was to develop EVERYTHING. It took 5 years for enough info to leak out of IBM and enough infrastructure and development to happen at outside companies like the Seagates and the component suppliers, but the reason it was 5 years instead of 20 is that there was an awful lot of technology that IBM developed that ended up leaking. Given the challenges involved in incorporating the MR head- 5 years not bad.

- Tom was the IBM product development manager of Corsair- the first HDD product to use MR heads. Integration was incredibly difficult and took a lot longer than it was supposed to. Given those challenges in integrating MR heads vs. thin film heads, 5 years isn't terribly long, especially in that time frame.

- If someone did not invest in their own R&D on integration, they wouldn't have survived- they would either run out of money or they would have shipped something with a major problem into the marketplace and the market would have taken them out. Several companies failed making that MR head transition.

- Broader R&D gives you a better chance of picking the right technology.

- In 1997, he went to Seagate- after IBM had cut drive business back dramatically, had cut funding IBM R&D (especially for disk drives)- IBM was in the throes of transitioning from a WI business into a services and software business. Al Shugart (Seagate founder) said that IBM was essentially getting out of the disk drive business, they've cut research dramatically if a US firm doesn't make a major investment in HDD research, particularly in component research in a major way, they will lose the entire business to the Far East.

- His job was to set up a research organization within Seagate (which Mark eventually headed) to replace what was leaving at IBM as they exited disk drive research. This was all based on Al Shugart saying that you needed to be VI-ed to succeed in this business and do R&D to keep the industry in the US.

- In technology industries, you have to make investments in research.

- The way he responded to Al was yes I'll take the job, need to find someone to head the research organization.

- Last point: He had to find someone to lead R&D on Seagate- at the time, spending was very low on long-range R&D (less than 1% on R&D that would take more than 2 years). They increased spending 20% on R&D that would take longer than 5 years, 10% increase in spending on R&D that would take 2-5 years (to create an innovation pipeline) and the rest on advanced technological development (who took R&D output and transitioned it to product development). Shut down a few design centers to pay for research. This is why Seagate grew so much while **___** was there (his budget was $50mm while he was there).

- Wasn't that difficult as it seems because they had purchased Imprimis and Conner Peripherals so they had 3 different product development teams but they never integrated those together. Even things as fundamental as to which way should a disk spin was different in each one, so they formed a platform strategy to leverage head platforms and disk platforms and drive platforms, and silicon platforms (like auto industry does).

- Customer interface side didn't change as a result of this. Example of a failure in a sense was that there was a set of thinking, particularly at Seagate, due to focus on 5 year and 10 year horizons, and people felt that there would need to be a need for smaller and smaller drives so they started to do work on 1.8" drives. But they didn't anticipate other technologies (moving as fast in silicon areal density increases as it did in drive business- wasn't long before you could use flash in a cell phone or a camera), like flash, replacing them. Can get blindsided if you don't truly understand where your competition is coming from in the future, even though the tech is moving in parallel.

- Both he and **___** think that they'll move from flash back to disk drives over the next 10 years.

A.5 INTERVIEWEES' CHARACTERIZATIONS OF DIFFERENT TECHNOLOGICAL CHANGES

Technology change	Interview 1	Interview 2	Interview 3
MR heads	1. "2 companies that did MR head technology (IBM and HP) did tech for MR head- IBM version was reverse engineered by the rest of the industry (they waited for product to come out, took it apart- spent 2-3 years before they mastered the tech and they could commercialize MR heads." 2. "H-P chose not to make its own technology- chose to use Headway in California- outsourced to Komag affiliate Headway- made wafers. Established a 3 way partnership- H-P, Seagate, and Headway. Headway (later purchased by TDK- only head maker around today) made wafers, H-P provided technology. Seagate then took the wafers, did HGA, kept some for itself, gave rest to H-P. During this process, Seagate learned to make the MR heads by watching Headway (benefited from 20 yrs of research at H-P)."	1. "During the evolution, there were lots and lots of changes: 3 big changes: 1. change from a particulate disk (paint) to thin film disk media 2. change from conventional recording head to a MR (magneto resistive) head 3. change from giant control units to a small, relatively compact circuit electronics thing you put on the drive." 2. "my own specialty: thin film head and originally it was a regular magnetic conductor thin film head, although he started working on both of them in 1969 or so, 1970. So as far as I'm concerned, the thin film head, and the inductive head and the MR head are at pretty much the same time, but from a product point of view, MR head took 20 years (came out in 1991), thin film inductive heads was much earlier, at least 10 years earlier." 3. "The reason that the MR head was a bigger change than the thin film head was because the thin film head, in some sense, was a drop-in replacement for the previous inductive head, which is a ferrite head, which is pretty much a drop in replacement for the original metal head. If you showed someone who worked on the original heads and you showed them the ferrite head which was a magnetic material and smaller, and then you showed them the thin film head, well, we got rid of the ladies with the needles who were trying to wind wire around an infinitesimal gizmo and replaced it with thin film fabrication techniques. But they're all essentially the same, so there's no trouble- if you understood one, you would have no trouble understanding the other. And the MR head, of course, was a different animal entirely."	1. "MR heads, thin film heads and media- difficult technology transitions for the industry to make, but at the time, in the early days, IBM was very pre-eminent in those technologies, in terms of their research understanding. The problem they had was that they couldn't translate that to product development. So there was this kind of cultural barrier between IBM research and product development that slowed the transition of technology from research into product development. One of the huge issues for the enterprise business was that reliability was king- using the new technology was a very dangerous thing. If you moved to a new technology too quickly into a product in the enterprise business and it was embryonic and had some kind of teething pains then you ended up populating enterprise systems with a problem that was going to be very very costly to fix. So there was a natural reluctance to new technology going rapidly from research to products." 2. "MR heads actually got introduced first in IBM in the low end of the business (he was the product development manager at the time for that). It was introduced in a product called Corsair which is a 3.5" 8 disk stack disk drive- standard form factors. So IBM's introduction of MR heads into disk drives to the world actually happened in lower end business. Not necessarily PCs but intermediate systems and then PCs came a bit later. By the time PCs were there, IBM was

4. “I used to give the newcomers a kind of little lecture on why the MR head turned everything upside down. Previous heads, when you went from one generation to another, was a big deal in head department, and you also had to talk to the guys who had to decide what voltage of currents to run through it, but other than that, they’re all pretty much the same, they affected mostly the head department. When we went to the MR head, we had to change of course, the head department, change the disk, because, well I can tell you why, but we had to coat the disk. We had to change the electronics, the equalization as it’s called- the signal was different. We had to change the servo dept because up until that time, the same recording head wrote the track and read it (a single head device). But an MR head only reads, so you had to build it with an inductive head stuck on top of it. And since they’re never exactly in the same alignment, you had to get the servo people to switch a little bit of track switch every time you switched between reading and writing, partly a big deal because by that time, even when you were writing, between that receptor you had to read the servo information which tells you where the head is positioned. So it changed all of that. Then you also had potential corrosion problems, so the people who were in charge of the atmosphere within the drive had to change what they were doing and then there was endless testing, and it turns out these heads were susceptible to electrostatic charge, static zap. So if the ladies wiggle their butt on the chair and get an electrostatic charge while assembling drive, it would blow up the head. So there was a whole new testing regime, a whole new manufacturing procedure. If I think about it more I’ll probably come up with other departments that were affected. But the short answer is, changing from a thin film to an inductive head was small potatoes compared to affecting everybody when you went to an MR head, and building disk drives in Japan, trying to get the low cost structure to solve this margin problem that I described before, and they were building 5.25” and 3.5” disk drives with older, Winchester technology in Japan for the internal PCs. The other issues IBM had was that anything that was made internal was kept internal, had trouble being willing to sell their technology.”

3. “When IBM introduced first MR heads into 3.5” disk drive business, they were never able to capitalize on it because they had a too high-cost infrastructure. So as MR heads became available from companies like Read Rite- later than IBM- significant amount of time- 3 years or more, might even be 5- because it was a very difficult technology. But IBM at the time would not sell its MR heads to anyone- Seagate even approached IBM to purchase MR heads and IBM said no.”

4. “Component suppliers did not work together, company like Seagate would source current production from several, maybe 3, head suppliers. So as the component suppliers made the transition from ferrite heads to thin film heads, and then the big difficult jump to MR heads took 5 years (which is actually not that bad- couldn’t have done it any faster)- Seagate would provide a test bed- did the system integration coordination.

5. “The MR heads required totally different set of electronics to drive it, the amplifiers and write drivers were seriously different and had to account for some pretty challenging issues with MR heads in early days- so Seagates of the world would be the coordinator of that technology. So they would figure out some of the anomalies in the MR head for example and go back to the

that's one of the reasons why the industry lagged behind a while."

5. "Here's another example: in a disk drive of those days, probably even still today, there are inevitable contacts between the heads and the disks. Because you just can't make a disk smooth enough, because you're flying so close, you could never get a speck of dust in there, but even so, any little ripple on the disk touches the head, and didn't affect the inductive head except it might wear it, but an MR head was thermo transient (drove electronics crazy), so there was a long and difficult set of work in the electronics side and in the channel side, to deal with the thermo-transience. So they just didn't exist before that. Imperfections on the disk when head goes by, it actually mechanically touched, it didn't have to be a magnetic particle it touched, often it was just a speck of something that was there in the disk manufacturing process, but as it went by the head, it caused a little thermo blip indistinguishable from a magnetic blip, so it drove the channel crazy."

6. "So all the air bearing people and wear and reliability people had to worry about that, but they knew what their orders were. But the MR head was a new set of orders. In addition to all of that, there was more."

7. "When you went to an MR head, you not only had to lubricate it and keep it dry, but you also had to put in an insulating layer because when the head hit the disk, it was actually an electrical short and you can't have that (used carbon overcoat had hard carbon, an insulator to protect MR heads from shorting out when they touch the disk)."

8. Made first MR heads in 1970 and first working inductive heads in 1970s- recognized that MR heads not an obvious choice for HDD- with an inductive head, you get a voltage out that's proportional to the rate at which bits go by (the velocity of the disk).

supplier with the right electronics and say "I need this to be current sourced in this way, I need the read amplifier to be able to overlook a certain kind of noise, so there was that kind of system integration, a very technical system integration function that was provided by companies like Seagate, Maxtor and Western Digital."

6. "The 20 years IBM took to develop MR heads was to develop EVERYTHING. It took 5 years for enough info to leak out of IBM and enough infrastructure and development to happen at outside companies like the Seagates and the component suppliers, but the reason it was 5 years instead of 20 is that there was an awful lot of technology that IBM developed that ended up leaking. Given the challenges involved in incorporating the MR head- 5 years not bad.

7. "Tom was the IBM product development manager of Corsair- the first HDD product to use MR heads. Integration was incredibly difficult and took a lot longer than it was supposed to. Given those challenges in integrating MR heads vs. thin film heads, 5 years isn't terribly long, especially in that time frame."

8. "If someone did not invest in their own R&D on integration, they wouldn't have survived- they would either run out of money or they would have shipped something with a major problem into the marketplace and the market would have taken them out. Several companies failed making that MR head transition."

		With something like a tape drive, which is 100x lower velocity, the signal is a 100x smaller, the MR head doesn’t care, it’s independent of speed. Early heads were used for magnetic stripe cards at Macy’s to read price tags just like credit cards, sensing magnetic bubbles, tape drives much earlier. IBM made these- so very broad R&D and product placement. Problem solving: That’s when you would use your broad R&D to decide what to use to give you transfer rate, capacity and reliability demanded.” 9. “With every tech change there were people who argued for keeping the old technology. Every time a new product cycle started, they’d name a product manager to talk to R&D for problem solving- manager would have to decide what to use after talking to R&D. So example of a problem: too small of a signal, having trouble writing, need more capacity or reliability- MR heads were the answer.” 10. “MR heads were on the table for a long time before they were picked up. The product manager did not want to be the first guy to use a new technology, because it cost an enormous amount to do that, came out of his budget, cost to his profit, and lost reliability, took a long time to get this back.” 11. “R&D- Consultants to product developers, invented things on the side (MR heads and thin film inductive heads fell into this category).” 12. “By the time MR heads came out- patents were expiring for that tech. When you patent something, telling the world what you’re doing. If you know something will take a long time, so you’re torn- do you patent? What about coworkers who leave (could patent it at next company)? Can’t publish without patenting. Can patent things you can’t make.”	
Thin Film Media	“IBM was late on film disk- even though they’d been working on it since mid-	1. “During the evolution, there were lots and lots of changes: 3 big changes: 1. change from a particulate	1. “Knew tech changes were coming but couldn’t move fast enough for 2 reasons: 1.

1960s- but were late- it was introduced by another firm in 1983, was not introduced by IBM in 1988."

disk (paint) to thin film disk media 2. change from conventional recording head to a MR (magneto resistive) head 3. change from giant control units to a small, relatively compact circuit electronics thing you put on the drive."

2. "There was one major evolutionary change- the thin film disk- to get rid of the paint, and that was very difficult for the disk people and the reliability people who had to worry about lubricating and wear and so forth, but it didn't affect the other departments very much."

3. "More departments than you know. Tribology (science of corrosion and wear- deal with reliability)- head crash group- when they went from particulate disks (iron oxide- not very magnetic) to thin film disks- big change for them. They had to work really hard to come up with a way of lubricating a metal- once you go to metallic (iron oxides not very magnetic- went to thin film because they needed stronger magnets)- head crashes, nicks the protective coat on the disk and then corrodes (rust) the disk."

reluctance on part of product development team to move these new technologies into the products, because they had a huge install base that required enormously mature technology, they wouldn't risk putting an embryonic technology into the products because the business impact would be so great. At that particular time they were coming off of a very serious problem with particulate media- and even conventional heads- where there was some kind of vapor in the manufacturing process that was changing the properties of the lubricant on the media, and they would get stuck heads in the field, so the customer would shut the drive down, and restart, or when they went to restart, it would rip the heads off the suspension- so this was at about the same time that the industry was transitioning to thin film media and thin film heads. So the product development team was exceedingly worried about moving new technology very rapidly for fear of creating another hugely expensive- and this was hundreds of millions of dollars to fix that problem with the sticking heads. The industry struggled with this as well. (2) Cultural divide between IBM research and product development. IBM research folks had been run very very independently, they had independent funding, they worked on whatever they wanted to work on, and IBM figured out that they really needed to take advantage of that great resource in IBM research, and so they began to assign IBM research members to product development teams to build a pipeline of translation from IBM research development into product development. That helped, but it was too little too late. And it took a while for the research team- many of them didn't really want to work on

			product development. And there was a little bit of arrogance on the side of the IBM research team as well. Product development folks made to feel like second-class citizens.”
Thin Film Inductive Heads		1. “my own specialty: thin film head and originally it was a regular magnetic conductor thin film head, although he started working on both of them in 1969 or so, 1970. So as far as I’m concerned, the thin film head, and the inductive head and the MR head are at pretty much the same time, but from a product point of view, MR head took 20 years (came out in 1991), thin film inductive heads was much earlier, at least 10 years earlier.” 2. “R&D- Consultants to product developers, invented things on the side (MR heads and thin film inductive heads fell into this category).” 3. “Thin film inductive- a process more than knowledge and process patents were not enforceable (although did get a good patent out of that- patent the wrinkles that come out of the process- the shape of the little magnetic pole tips and the shape of the back of the thing- patent what you got out of the process- what was needed to make something work)”	1. “Knew tech changes were coming but couldn’t move fast enough for 2 reasons: 1. reluctance on part of product development team to move these new technologies into the products, because they had a huge install base that required enormously mature technology, they wouldn’t risk putting an embryonic technology into the products because the business impact would be so great. At that particular time they were coming off of a very serious problem with particulate media- and even conventional heads- where there was some kind of vapor in the manufacturing process that was changing the properties of the lubricant on the media, and they would get stuck heads in the field, so the customer would shut the drive down, and restart, or when they went to restart, it would rip the heads off the suspension- so this was at about the same time that the industry was transitioning to thin film media and thin film heads. So the product development team was exceedingly worried about moving new technology very rapidly for fear of creating another hugely expensive- and this was hundreds of millions of dollars to fix that problem with the sticking heads. The industry struggled with this as well. (2) Cultural divide between IBM research and product development. IBM research folks had been run very very independently, they had independent funding, they worked on whatever they wanted to work on, and IBM figured out that they really needed to take advantage of that great resource in IBM research, and so they began to

			assign IBM research members to product development teams to build a pipeline of translation from IBM research development into product development. That helped, but it was too little too late. And it took a while for the research team- many of them didn't really want to work on product development. And there was a little bit of arrogance on the side of the IBM research team as well. Product development folks made to feel like second-class citizens." 2. "Thin film head transition came at a time before or simultaneously with the embryonic development of the PC business. So thin film heads and thin film head media were just transitioning at that time, so that's a time when IBM was living that problem (would have had to test the new tech in enterprise systems first)."
Form factor changes	1. "Differences among companies in recognizing new markets: i.e. Seagate saw IBM PC as a market, even though IBM did not, Integral Peripherals saw mobile opportunity." 2."Usually new entrants/startups found the market for new form factors- then big firms entered when it got big enough. Only after they demonstrated that these moves were significant did established firms move to offer that product as well." 3. "Latecomers made it to the market eventually (IBM was a latecomer to mobile market, but still got 50% of the market when they entered)- but even with successive changes, firms had trouble judging what markets to go into. 2 instances where IBM pioneered- RAMAC and the microdrive which had a short	1. "Form factors: every new generation of disk drives shrank the components inside them. If you wanted to cut the loop on the areal density, you had to cut the track length in half and the bit length in half, and in the early days, you didn't want a time, you first cut the track, and put out a generation of drives with twice the capacity. And then you put twice as many bits per inch along the track and that would be the next generation. Then you would go back to having the tracks again. And each time you do that, you have to make the magnetic grains on the disk had to be finer to keep the signal from getting read, you made the gap in head narrower to get more BPI along it. You had to make the width of the head half so you could get twice as many tracks per inch. But those were just evolutionary and they went on for many years. Everyone knew what their job was, you would have a smaller signal so you had to do something to filter out the noise. If you were increasing the linear density you had to fly closer by a factor of 2. So all the air bearing	1. "IBM kind of figured it out, though they had another problem- it was a centrally managed company- all the major decisions concerning investments and strategy came out of Armonk, and so the operating divisions couldn't manage their businesses independently- everything had to go through Armonk for final approval make decisions. They had a business process and structure issue that just slowed them down so much, that they didn't respond quickly enough even though they really could see it coming. It was fascinating to watch and probably still have today one of the most sophisticated predictive capabilities in their organization in terms of where technologies are going, where the business is going, where the markets are going. They understand all of that, but just couldn't make the transition fast enough." 2. "So speed was a problem and

life towards the end of the time they were in the industry- everything else they waited for others to pioneer."

people and wear and reliability people had to worry about that, but they knew what their orders were."

2. "3rd big change- evolutionary- Electronics- changed from vacuum tubes to transistors to integrated circuits to million transistor integrated circuits and suddenly something as big as a refrigerator was now on a chip, and you can actually put it in a little disk drive instead of in a separate giant box. Evolutionary change- not a single product change like MR heads. If you wanted to point at something- 8" and 5.25" drives (because before that the disks were huge with giant control units)- huge shrinking in 1 product. Allowed a lot of new applications for disk drives, not just data center at the bank anymore."

that's sort of the high level overview of the business and infrastructure issue that IBM was dealing with in the early 90s/late 80s."

3. "They started out- not selling into the OEM business. The 5.25" disk drives were developed for internal IBM system platforms, as well as the 3.5" disk drives, and those divisions were not allowed to OEM those devices. So IBM was protecting their technology by not selling it to other companies. They were trying to protect their PC business, for example, by only allowing Fujisawa, Japan to ship disk drives for IBM PCs, wouldn't let them sell them to HP or Atari or anyone else in the early days. They finally changed that but it was again too late. This gets back to everything getting driven out of Armonk, so these were strategic decisions that were made at the company but the decisions came too late. The decision to participate in the OEM market as a supplier of components came too late. It allowed the myriad of other disk drive developers and manufacturers to get a strong foothold because IBM could not get their cost structure under control fast enough."

4. "I really think that the long term strategists could see the emergence of the PC market pretty early. In fact IBM did a machine called the 5100 which was a basic ATL machine that weighed 50 lbs and would fit underneath the seat of an airplane, but that was really the first commercial portable computer. Albeit not very portable in today's standards. But that came before PCs. SO IBM could see this coming and set up PC business as an independent company because they could see it coming. They saw it coming but they just couldn't react fast

enough. Of course the margins in the PC business got- they went from 20% to 5% as many many new companies got involved in it."

5. "Margins were not there for new markets to make it worth entering. They exited disk drive business eventually for that reason- because the margins were not there. And they said- this was all part of a major transformation of IBM from a major vertically integrated company focused on hardware to a sales and services kind of company, with software. IBM made this huge huge transition, in the 90s, driven by the fact that they just couldn't manage the low margins, couldn't survive in that world, so they changed the direction of the company in a profound way, and I'm convinced that they would have failed if they hadn't done that. It's unusual for a company as old as it was at the time, 70-80 years old at the time, to make this huge transition, and its business model, driving 400,000 people in a new direction. So again a result of IBM being able to look at the future pretty well, they just realized that they were never going to get their cost structure to the point where they could survive the low margins in the PC business, so they decided to exit it and go in a new direction."

6. "He thinks they moved into the PC business thinking that margins were going to be x%, and they ended up being x-20% or something like that."

7."High volume commodity business- IBM didn't understand. They didn't think they thought the PC business was going to become so commoditized with the resulting margin erosion that happened. Once they figured that out, they just got out, closed the business down."

8. “Emerging technology- there are early adopters and the volumes are low. Which is why big companies like IBM will move late into a market. It’s a matter of scale, so in the early days- IBM didn’t think it was worth going after 3.5”, 5.25” disk drives. I remember the discussions- “oh, there’s not going to be enough volume there. There’s an arrogance in the enterprise, high end disk drive business that the 5.25” drives were second rate and didn’t have the reliability that was needed, they were never going to make it.”

9. “For small startups, what seemed small to IBM (50K units/yr or even 10K/yr) was a big deal to a startup. Seagate was Al Shugart in a garage. Able to grow their infrastructure and scale it as the business grew (didn’t have millions of dollars in salaries to pay every year), whereas IBM and other big firms like Imprimis started with a huge amount of overhead and just didn’t think this low end was going to grow as quickly as it did.”

10. “i.e. Conner Peripherals supplying disk drives as a supplier to H-P for PCs- the big system houses like H-P would be trying to enter a new market, like a notebook, so they would go back to the drive supplier, in this case, Conner Peripherals, asking for a smaller drive, they were going to scale down the size of a computer to the point where it can become even more portable so I need a smaller disk drive. (JEAN NOTE: they found out about the new markets from their customers (H-P) who wanted to make a laptop or notebook or whatever). The other thing that happened of course was the areal density was doubling every 12-18 months, so the capacity of a disk drive soon

outpaced the needs of a very low end entry level computer, and so the size and power requirements of the silicon was dropping at the same Moore's Law rate, so it became obvious to many people that if you project that into the future who thought notebooks would be possible, even if a whole bunch of people did not think the market would be anything. Same argument people used when the markets for PC started- low level, entry-level device has a- only meets a modest set of requirements but it's enough to get it started."

10. "The system houses that were looking to do notebooks or whatever emerging markets would go to their supplier and ask for smaller drives. Then Maxtor's (or whoever's) marketing people would go back to product developers and see if it was possible and start a new business line."

11. "The folks at Seagate slow at this- Conner much better (did early 2.5" drives)- bought Conner (and it's 2.5" disk drive business) to solve this problem of late market entry."

12. "These startup companies had very little advanced technology work- were pretty market-driven. They'd wait for someone to ask them for something smaller. Margins were so low- they couldn't afford the R&D unless they know the market is there. Seagate was a very large company when 2.5" business started, Conner was a startup (first product was 2.5" drive)- Innovator's Dilemma type thing where new startup came in at very low end and established company was late to come to market. The reason it happens, in the generic sense is that lots of startups (9 out of 10) fail- because they picked the wrong market, usually."

13. “Flaw in IBM’s thinking- unwillingness to participate in OEM business at any level- disk drive or component level- was a major error. IBM would not supply any components to the other HDD firms- wanted to protect their IP- but someone could reverse engineer the technology. So protecting your IP that way is fleeting- doesn’t last very long.”

APPENDIX B

PATENT CLASS AND SUBCLASS DATA

A sample of relevant patent subclasses (from the US Patent Office) under each of the three relevant classes of HDD patents: 360, 369, and 428.

B.1 PATENT CLASS 360

Patent Class 360: DYNAMIC MAGNETIC INFORMATION STORAGE OR RETRIEVAL

1 RECORDING ON OR REPRODUCING FROM AN ELEMENT OF DIVERSE UTILITY
2 .Card
3 .Motion picture film
4 MANUAL INPUT RECORDING
5 RECORDING FOR SELECTIVE RETENTION OF A SPECIAL OCCURRENCE
6 RECORDING COMBINED WITH METERING OR SENSING
7 RECORDING FOR MONETARY DELAY OF AN ANALOG SIGNAL
8 RECORDING FOR CHANGING DURATION,FREQUENCY OR REDUNDANT CONTENT OF AN ANALOG SIGNAL
12 RECORDING OR REPRODUCING FOR AUTOMATIC ANNOUNCING
13 RECORD EDITING
15 RECORD COPYING
16 .Contact transfer
17 ..With magnetic bias
18 RECORDING OR REPRODUCING PLURAL INFORMATION SIGNALS ON THE SAME TRACK

20 .Frequency multiplex
21 .Head gap azimuth multiplex
22 SPLITTING ONE INFORMATION SIGNAL FOR RECORDING ON PLURAL DISTINCT TRACKS OR REPRODUCING SUCH SIGNAL
23 .Time division
24 SPLITTING, PROCESSING AND RECOMBINING ONE INFORMATION SIGNAL FOR RECORDING OR REPRODUCING ON THE SAME TRACK
25 CHECKING RECORD CHARACTERISTICS OR MODIFYING RECORDING SIGNAL FOR CHARACTERISTIC COMPENSATION
26 ELECTRONICALLY CORRECTING PHASING ERRORS BETWEEN RELATED INFORMATION SIGNALS
27 RECORDING OR REPRODUCING AN INFORMATION SIGNAL AND A CONTROL SIGNAL FOR CONTROLLING ELECTRONICS OF REPRODUCER
28 .Reference carrier to control demodulator
29 MODULATING OR DEMODULATING
30 .Frequency
31 MONITORING OR TESTING THE PROGRESS OF RECORDING
32 CONVERTING AN ANALOG SIGNAL TO DIGITAL FORM FOR RECORDING; REPRODUCING AND RECONVERTING
39 GENERAL PROCESSING OF A DIGITAL SIGNAL
40 .In specific code or form
41 ..Nonreturn to zero
42 ..Phase code
43 ..Multi-frequency
44 ..Intra-cell transition
45 .Pulse crowding correction

B.2 PATENT CLASS 369

Patent Class 369: DYNAMIC MAGNETIC INFORMATION STORAGE OR RETRIEVAL

Examples of subclass definitions relevant to HDD:
13.01 STORAGE OR RETRIEVAL BY SIMULTANEOUS APPLICATION OF DIVERSE TYPES OF ELECTROMAGNETIC RADIATION
13.02 .Magnetic field and light beam
13.03 ..Initializing
13.04 ..Erasing
13.05 ..Reading
13.06 ...By transferring magnetic domain between layers
13.07 ....Three or more magnetic layers
13.08 .....Changing size of magnetic domain

13.09 ....Changing size of magnetic domain
13.1 ..Three or more magnetic states
13.11 ..Positioning of transducer assembly for storage or retrieval
13.12 ..Relative positioning of transducer assemblies
13.13 ..Integral transducers
13.14 ..Magnetic field generation
13.15 ...Leakage magnetic field
13.16 ...Overwriting
13.17 ...Magnetic field transducer assembly
13.18 ....Permanent magnet
13.19 .....Rotating magnet
13.2 ....Operative location positioning of transducer assembly
13.21 .....During load and unload of storage medium
13.22 ...Magnetic field generating circuit
13.23 ....Conductor coil
13.24 ..Light beam generation
13.25 ...Overwriting
13.26 ...Setting light beam power level
13.27 ....Based on referenced test signal

B.3 PATENT CLASS 428

Patent Class 428: STOCK MATERIAL OR MISCELLANEOUS ARTICLES
Examples of subclass definitions relevant to HDD:
800 MAGNETIC RECORDING COMPONENT OR
STOCK
810 .Magnetic head
811 ..Magnetoresistive
811.1 ...Having tunnel junction effect
811.2 ...Multilayer
811.3 ....Super lattice (e.g., giant magneto resistance (GMR) or colossal magneto resistance (CMR), etc.)
811.4 ...Single film
811.5 ...With defined structural feature
812 ..Magnetic layer composition
813 ..Substrate composition
814 ..With protective film
815 ..With defined laminate structural detail
815.1 ...Head with slider structure
815.2 ...With head pole component

816 ..With interlaminar component
(e.g., adhesion layer, etc.)
817 .Magneto-optical media stock
818 ..Multiple magnetic layers, at least one of which is magnetooptic
819 ...Unit structure (i.e., three or more differing magnetic layers
in series)
819.1 ....Reoccurring unit structure
819.2 ....Only three adjacent magnetic layers form series
819.3 ....Only four or six adjacent magnetic layers form series
819.4 .....Magnetic layers and at least one intervening nonmagnetic layer (e.g., antiferromagnetic, dielectric,etc.)
820 ...Only two magnetic layers, at least one of which is magnetooptic
820.1 ....Magnetic layer pairs separated by single nonmagnetic (e.g., antiferromagnetic, dielectric,etc.) layer
820.2 ....Adjacent magnetic layers
820.3 .....Having in-plane orientated magnetization
820.4 .....Magnetic layer composition specified
820.5 .....Specified performance related property (e.g., Kerr rotation, etc.)
820.6 ......Curie temperature
821 ..Single magneto-optic magnetic layer
822 ...Magneto-optic magnetic layer contains transition metal
822.1 ....Magnetic transition metal oxide in magneto-optic layer

APPENDIX C

LITERATURE REVIEW TABLES

C.1 LITERATURE REVIEW TABLE ON TECHNOLOGICAL, MARKET AND ORGANIZATIONAL SYSTEMS

Authors	**Systems Change**
Adner (2002)	market
Bryce and Dyer (2007)	market
Christensen and Rosenbloom (1995)	market
Danneels (2003)	market
Danneels (2004)	market
Jacobides et al. (2006)	market
Kim and Mauborgne (1999)	market
Porter (2008)	market
Rosenbloom and Christensen (1998)	market
Rothaermel (2001)	market
Rothaermel and Hill (2005)	market
Teece (1986)	market
Tripsas (1997)	market

MacMillan and Selden (2008)	organization
Aiken and Hage (1971)	organization
Amburgey et al. (1993)	organization
Barney (1991)	organization
Benner and Tushman (2002)	organization
Burgelman (1991)	organization
Cardinal (2001)	organization
Cattani (2005)	organization
Chesbrough (2005)	organization
Christensen and Overdorf (2000)	organization
Damanpour (1991)	organization
Dougherty and Hardy (1996)	organization
Dyer (1996)	organization
Eisenhardt and Martin (2000)	organization
Garud and Munir (2008)	organization
Hage (1999)	organization
Hannan (1984)	organization
Helfat and Leiberman (2002)	organization
Hillman et al. (2009)	organization
Iansiti et al.(2003)	organization
Katz and Allen (1982)	organization
King and Tucci (2000)	organization
Langlois (1997)	organization
Levinthal and March (1993)	organization
Macher and Richman (2004)	organization
Pierce and Delbecq (1977)	organization
Puranam et al. (2006)	organization

Rosenberg (1976)	organization
Rosenkopf and Nerkar (2001)	organization
Sandström et al. (2009)	organization
Smith et al. (2005)	organization
Thomond et al. (2003)	organization
Tripsas (2009)	organization
Tripsas and Gavetti (2000)	organization
Tushman and O'Reilly (1997)	organization
Tushman and Romanelli (1985)	organization
Volberda and Elfring (2001)	organization
Westerman et al. (2006)	organization
King and Tucci (2002)	organization and market
Cohen and Levinthal (1990)	organization and market
Macher and Richman (2004)	organization and market
Baden-Fuller and Morgan (2010)	organization and market
Chesbrough and Rosenbloom (2002)	organization and market
Christensen and Bower (1996)	organization and market
Gawer and Cusumano (2008)	organization and market
Brusoni et al. (2001)	technology
Glasmeier (1991)	technology
Henderson and Clark (1990)	technology
Jiang et al. (2010)	technology
Kapoor and Adner (2012)	technology
Rothaermel and Thursby (2007)	technology
Sosa (2011)	technology
Tushman and Anderson (1986)	technology
Adner and Kapoor (2010)	technology and market
Ansari and Garud (2009)	technology and market

Christensen (1997)	technology and market
Lazonick (1991)	technology and market
D'Aveni (2002)	technology and organization
Hoetker (2005)	technology and organization
Rosenbloom (2000)	technology and organization
Rothaermel and Boeker (2008)	technology and organization
Sosa (2009)	technology and organization
Yu and Hang (2009)	technology and organization
Taylor and Helfat (2009)	market, organizational, and technology
Hill and Rothaermel (2003),	market, organizational, and technology
Klepper and Simons (2000)	market, organizational, and technology

C.2 LITERATURE REVIEW TABLE ON KNOWLEDGE AND PRODUCTION BOUNDARIES

Authors	Year	Findings	Type of boundary
Kogut, B., Zander, U.	996	Def of knowledge boundaries: "It is not transaction costs, but the social knowledge embedded in the competence of individuals and the organizing principles of work that explains what firms are on the basis of what they know how to do. We propose that the boundaries of firms demarcate qualitative changes in the reservoir of social knowledge available to economic agents (i.e., people) because coordination and learning are developed within the organizational context of shared identities. This shared identity does not only lower the costs of communication, but establishes explicit and tacit rules of coordination and influences the direction of search and learning."	knowledge
Laursen K, Salter A	006	market knowledge enhanced by exposure to diversity of rivals and clients.	market knowledge
Taylor, A., & Greve, H. R.	006	"multiple knowledge domains produce novel combinations that increase the variance of product performance and that extensive experience produces outputs with high average performance."	market knowledge

Zhou, K. Z., Li, C.B.	012	"A firm with a broad knowledge base is more likely to achieve radical innovation in the presence of internal knowledge sharing rather than market knowledge acquisition. In contrast, a firm with a deep knowledge base is more capable of developing radical innovation through market knowledge acquisition rather than internal knowledge sharing." (our interpretation: firms more likely to spot emerging market opportunities for tech commercialization when exposed to different market stimuli.)	market knowledge
Miller, D., & Chen, M. J	994	Exposure to different market stimuli will have a negative effect on organizational inertia	market knowledge (prod diversity)
Miller, D., & Chen, M. J.	996	exposure to different markets, rivals, customers will increase a firm's market knowledge	market knowledge (prod diversity)
Abrahamson, E., & Fombrun, C. J.	994	Interorganizational phenomena-particularly beliefs widely shared by managers across related organizations-are also to blame for the collective failure of industries.	market knowledge (product diversity)
Ahuja, G., Lampert, C.	001	Experimenting with novel (i.e., technologies in which the firm lacks prior experience), emerging (technologies that are recent or newly developed in the industry), and pioneering (technologies that do not build on any existing technologies) technologies allow firms to create breakthrough inventions.	market knowledge (product diversity)
Barkema, H. G., & Vermeulen, F.	998	"A firm that leverages its technological capabilities into multiple businesses will be exposed to a richer set of demand characteristics (cf. Argyres, 1996a], rivals, suppliers, and partners than a firm operating in a single business. Leveraging technological capabilities into multiple businesses may also lead to economies of scale and scope, which may increase the returns from innovation while spreading the risks (Peteraf, 1993; Teece, 1982]. Hence, product diversity also fosters innovation."	market knowledge (product diversity)
Tallman, S., Li, J.	996	For a sample of large American industrial multinational enterprises (MNEs), it showed a consistent quadratic relationship between product diversification and MNE performance but minimal performance differences across different measures of international diversity.	market knowledge (product diversity)
Benner, M. J., & Tripsas, M.	011	"(1) prior industry experience shapes a set of shared beliefs that results in similar and concurrent firm behavior; (2) firms notice and imitate the behaviors of firms from the same prior industry; and, (3) as firms gain experience with particular features, the influence of prior industry decreases."	market knowledge and market production

Christensen, C. M., Rosenbloom, R. S.	995	“The value network--the context within which a firm competes and solves customers' problems--is an important factor affecting whether incumbent or entrant firms will most successfully innovate. In a study of technology development in the disk drive industry, the authors found that incumbents led the industry in developing and adopting new technologies of every sort identified by earlier scholars --at component and architectural levels; competency-enhancing and competency-destroying; incremental and radical--as long as the technology addressed customers' needs within the value network in which the incumbents competed. Entrants led in developing and adopting technologies which addressed user needs in different, emerging value networks. It is in these innovations, which disrupted established trajectories of technological progress in established markets, that attackers proved to have an advantage.”	market knowledge and market production
Christensen, C. M., Suarez, F. F., Utterback, J. M	998	“Results suggest that entry strategies that entail market risk (entering an emerging market with proven component techology- what the new entrants did and the established firms struggled with) may be less risky than strategies that entail technological risk (entering an established market with new component technology- what the established firms did).”	market knowledge and market production
Tripsas, M., & Gavetti, G.	000	"Little theoretical attention has been devoted in this tradition to understanding how managerial cognition affects the adaptive intelligence of organizations. Through an in-depth case study of the response of the Polaroid Corporation to the ongoing shift from analog to digital imaging, we expand upon this work by examining the relationship between managers' understanding of the world and the accumulation of organizational capabilities. The Polaroid story clearly illustrates the importance of managerial cognitive representations in directing search processes in a new learning environment, the evolutionary trajectory of organizational capabilities, and ultimately processes of organizational adaptation" OUR INTERPRETATION: firms' views of new markets are shaped by prior beliefs/cognition/experience in older markets, which can lead to erroneous decisions regarding features/performance for new product- not what customers want.	market knowledge and market production
Anderson, E., Schmittlein, DC.	984	Integration of sales force leads to asset specificity, difficulty of performance evaluation, and the combination of these two factors.	market production
Christensen, C. M.	997	Established firms paid attention to existing customers and their needs (chose to invest in expensive component tech), new entrants looked at new markets with different trajectories in performance requirements and addressed those markets.	market production
John, G., & Weitz, B. A.	988	“We saw that firms were less likely to use reseller channels when specific assets levels were higher. Similar shifts were observed for higher levels of environmental uncertainty and behavioral uncertainty.”	market production

Klein, S., Frazier, G. L., & Roth, V. J.	990	“An important contingency when deciding on channel structure in a foreign country is the ability of the market to limit the opportunistic tendencies of outside intermediaries. When the enforcement of contractual arrangements cannot be relied upon in the market, different degrees of forward integration are feasible alternatives. Other empirical results suggest that the firm may prefer use of intermediaries in a foreign market with high environmental adversity in order to cope with its inherent complexity and maintain flexibility. Channel volume, the use of shared channels, and country destinations also are shown to affect the nature of integration in channels in international markets.”	market production
Rothaermel, F. T.	001	“Incumbents may be in a position to adapt to radical technological change via interfirm cooperation with new entrants when the incumbents have complementary assets within their firm boundaries that are critical to commercializing the new technology. We find that an incumbent’s alliances with providers of the new technology are positively associated with the incumbent’s new product development and, in turn, new product development is positively associated with firm performance. At the industry-level, we show that incumbents exhibit a preference towards alliances that leverage complementary assets (exploitation alliances) over alliances that focus on building new technological competencies (exploration alliances). In addition, the cooperation between incumbents and new entrants may contribute to an improvement in incumbent industry performance.”	market production
Rothaermel, F. T., Hill, C.W.L.	005	“The type of complementary assets (generic versus specialized) needed to commercialize a new technology is critical in determining the industry- and firm-level performance implications of a competence-destroying technological discontinuity. Iincumbent industry performance declines if the new technology can be commercialized through generic complementary assets, whereas incumbent industry performance improves if the new technology can be commercialized through specialized complementary assets. An incumbent firm's financial strength has a stronger positive impact on firm performance in the postdiscontinuity time period if the new technology can be commercialized through generic complementary assets. An incumbent firm's R&D capability has a stronger positive impact on firm performance in the postdiscontinuity time period if the new technology can be commercialized through specialized complementary assets.”	market production
Tripsas, M.	997	"In this industry, specialized complementary assets played a crucial role in buffering incumbents from the effects of competence destruction"	market production
Christensen, C. M.	993	Defines disruptive change as a shift in the trajectory of performance improvement in established markets. New markets difficult for established firms to recognize.	market production and market knowledge
Ahuja, G., Katila, R.	001	In technological acquisitions, firms are exposed to a new knowledge base that will allow them to create unique recombinations of knowledge when the knowledge bases are combined.	technological knowledge

Butler, J. C., & Grahovac, J.	012	Knowledge boundary def: sum of all the individual knowledge, and the routines/rules/decision rights the firm uses to access that knowledge (more of a capabilities argument- have to have certain org structure/hierarchy in place in order to access knowledge stores)	technological knowledge
Carlile, P. R.	002	**Knowledge boundaries**: obstacle getting in the way of problem solving (specialized knowledge within the firm creates them): “The characteristics of knowledge that drive innovative problem solving within a function actually hinder problem solving and knowledge creation across functions. knowledge and learning is structured by the types of problems faced within a practice (Lave and Wenger (1991), Brown and Duguid (1991), and Orr (1996)). Knowledge is embedded in practice and also embedded in the technologies, methods, and rules of thumb used by individuals in a given practice.”	technological knowledge
Cohen, W. M., Levinthal, D. A.	990	"The ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commerciai ends is critical to its innovative capabilities. We label this capability a firm's absorptive capacity and suggest that it is largely a function of the firm's level of prior related knowledge."	technological knowledge
Feldman, M. S., & Pentland, B. T.	003	“We argue that the relationship between ostensive (structure) and performative (action) aspects of routines creates an on-going opportunity for variation, selection, and retention of new practices and patterns of action within routines and allows routines to generate a wide range of outcomes, from apparent stability to considerable change.”	technological knowledge
Fleming, L., & Sorenson, O.	001	If a firm's R&D department has experimented with different component combinations, they may be able to incorporate componet changes faster because of the knowledge generated from their previous experimentation.	technological knowledge
Garicano, L., & Wu, Y.	012	**Def of knowledge boundaries**: knowledge here seems more task specific- each individual does a task and has the knowledge to complete that task, and there is knowledge sharing amongst individuals to complete new tasks that require combined knowledge. Knowledge that can be codified can be outsourced, while the more tacit stuff cannot be because it’s too costly to communicate it (KBV approach?). Uses communication as a coordination mechanism (works well with our interaction term argument). “knowledge-based production, knowledge is the main input. In this paper, we focus on the type of knowledge that satisfies two conditions: (1) knowledge that is used to solve specific problems, e.g., know-how or expertise; and (2) knowledge that is embodied in the human mind and is thus talent.”	technological knowledge
Grant, R. M.	996	Knowledge is viewed as residing within the individual, and the primary role of the organization is knowledge application rather than knowledge creation. Org knowledge= knowledge of many individuals that can be used for production. Knowledge that is difficult to share efficiently across firm boundaries will be integrated within firm.	technological knowledge
Sorenson, O., McEvily, S., Ren, C. R., & Roy, R.	006	"To attain broad scope, firms must repeatedly explore outside the boundaries of their current niche. Firms with broad niches therefore operate under a set of routines that repeatedly propel them into new market segments, expanding their niche."	technological knowledge

Tushman, M. L., Anderson, P.	986	describe a competence-destroying technological discontinuity as a situation where the processes, skills, and knowledge bases for an older technology are no longer relevant or have become dramatically less valuable in a particular market	technological knowledge
Yayavaram, S., Ahuja, G.	008	"Results show that a nearly decomposable knowledge base increases the usefulness of the inventions generated from it, as measured by patent citations, and also the knowledge base's malleability or capacity for change." (our interpretation: firms that are able to decompose knowledge/have coupling knowledge about different components will be better able to anticipate interactions as technology changes)	technological knowledge
Zander, U., Kogut, B.	995	"The determinants of the time to imitation are found to be the extent to which knowledge of the manufacturing processes is "common" among competitors, and the degree of continuous recombination of capabilities leading to improvement of the product or the manufacturing process."	technological knowledge
Sorenson, O.	003	"Firms face a trade-off. In stable environments, vertically integrating severely limits the organization's ability to learn by doing because boundedly rational managers find the optimization of operations difficult when making highly interdependent choices. As the volatility of the environment increases though, integration can facilitate learning-by-doing by buffering activities within the firm from instability in the external environment. Thus, firms with a high degree of interdependence suffer less in these environments." ALSO: "Whereas nonintegrated firms must respond to the actions of outside producers, integrated firms have the ability to direct the actions of internal suppliers. Consider the example of Intel and IBM mentioned above. While a firm that sources its CPU from Intel must adapt to whatever Intel chooses to do (or adapt by locating a new supplier), IBM can order its captive unit to refrain from making radical changes until other parts of the organization have the capacity to accommodate the change. Hence, by increasing the predictability of future development paths and component supplies, vertical integration reduces the firm's exposure to external volatility."	technological knowledge and techhological production
Balachandra, R.	002	Modular design allows firms to outsource production, but component changes create interface changes that cause firms to have to redsign products.	technological knowledge and technological production
Brusoni, S., Prencipe, A., Pavitt, K.	001	“We show that multitechnology firms need to have knowledge In excess of what they need for what they make, to cope with imbalances caused by uneven rates of development in the technologies on which they rely and with unpredictable product-level interdependencies. By knowing more, muttitechnology firms can coordinate loosely coupled networks of suppliers of equipment, components, and specialized knowledge and maintain a capability for systems integration.”	technological knowledge and technological production
Ciravegna, L. M., G.	012	Firms cannot outsource core design development, because it creates system integration issues (Firms need knowledge re: the component technologies they outsource or they will not be able to integrate them into their design, and address customer needs/performance requirements.)	technological knowledge and technological production

Granstrand, O., P Patel, and K. Pavitt	997	Large firms are more diversified in the technologies that they master than the products that they make and that their technological diversity has been increasing while they have typically been narrowing their product range.	technological knowledge and technological production
Hoetker, G.	005	Firms would prefer to use suppliers they already have relationships with than that have the most tech prowess, suggesting that communication between R&D and manufacturing is essential when technology changes.	technological knowledge and technological production
Kapoor, R., Adner, R	012	"vertically integrated firms had, on average, a faster time to market for new product generations than nonintegrated firms. The performance benefit that firms derived from vertical integration was greater when the new product generation was enabled by architectural change than when it was enabled by component change. We also find that although many nonintegrated firms extended their knowledge boundaries by developing knowledge of outsourced components, the performance benefits from such knowledge mostly accrued to "fully nonintegrated" firms (i.e., those that did not vertically integrate into any upstream component), rather than "partially integrated" firms (i.e., those that vertically integrated into some components but not others)."	technological knowledge and technological production
Negro, G., Sorenson, O.	006	"Vertical integration appears to change the dynamics of competition in two ways: (i) it buffers the vertically integrated firms from environmental dependence and (ii) it intensifies competition among non-integrated organizations." (our interpretation: firms that make their own supply may be able to develop the competency to manufacture/integrate new technology faster than waiting for outside suppliers).	technological knowledge and technological production
Prencipe, A.	997	Aircraft engine manufacturers retain technological knowledge about components where production is fully outsourced.	technological knowledge and technological production
Takeishi, A.	002	"For regular projects, it is more important for the automaker to have a higher level of architectural knowledge (how to coordinate various components for a vehicle) than of component-specific knowledge, which is supposed to be provided by the supplier. However, when the project involves new technology for the supplier, it is important for the automaker to have a higher level of component-specific knowledge to solve unexplored engineering problems together with the supplier. In innovative projects, effective knowledge partitioning seems to demand some overlap between an automaker and a supplier, rather than efficient and clear-cut boundaries that are optimal for regular projects."	technological knowledge and technological production
Adner, R., Kapoor, R.	010	Because vertical integration mitigates contractual hazards but not necessarily technological challenges, the shifting balance of technological and contractual uncertainty will increase the benefit from vertical integration over the course of the technology life cycle. So vertical integration is more effective after a technology has reached maturity, rather than during its emergence.	technological production

Afuah, A.	001	After a tech change (competence destroying), firms that are VI-ed into new tech will perform better than firms that are not. Firms that were VI-ed into old technology will be worse off than those firms that were not.	technological production
Arrow, K. J.	975	Uncertainty in the supply of the upstream good and the need for information by downstream firms makes VI a good choice.	technological production
Balakrishnan, S., Wernerfelt, B.	986	General uncertainty makes VI more attractive, but one particular kind (possibility of tech obsolescence) makes VI less attractive.	technological production
Funk, J.	009	Improvements in one area change the tradeoffs that exist between price and different dimensions of performance and between various design choices and thus lead to technological discontinuities in system design.	technological production
Harrigan, K. R.	984	avoid integrating into manufacturing if assets are in danger of becoming technologically obsolete	technological production
Harrigan, K. R.	985	"Positive changes in sales growth (demand uncertainty), particularly those associated with obsolescence from rapid technological change, discourage integration."	technological production
Jones, G. R., & Hill, C. W. L.	988	Strategy-structure choice (defined by TCE) is influenced negatively by tech uncertainty. "Thus, as a consequence of technological change, firms may change strategy, moving from related to unrelated diversification when technology is in ferment and moving the opposite way when it stabilizes."	technological production
Rosenberg, N.	976	"technological progress in one component may alter what is needed from other components within a device, forcing firms to make architectural changes in order to improve overall device performance"	technological production

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